Master Thesis

Master's degree in Industrial Engineering

Feasibility analysis and simulation of a renewable energy system in Barcelona

MEMORANDUM

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Summary of figures

Summary of tables

Summary of charts

On one hand, I would like to express my gratitude to all my lab teammates from the EPSE Lab located at the Incheon National University campus for the warm welcome I received when I arrived at Korea and all the support I received from them when I was trying to settle myself down. Specially, I would like to remark professor Jiyong Kim's patience and kindness to solve my doubts and teach me and guide me through this project.

On the other hand, I would like to thank the unconditional support of my family who, despite the distance, has always helped me. Also, I would like to mention my friends from Korea, my buddy Jun In Ho (David) and the people I met at the dormitory where I have been staying for those months, who have been my new family during my stay in this amazing country.

Abstract

In order to sum up the whole work done here, it should be explained with a fast overview, the contents that are going to appear below.

The main purpose of this project is to reduce Barcelona's dependency of fossil fuels trough the installation and analysis of a renewable energy model developed at the Incheon National University Campus (EPSE Lab) that would fit the city according with its resources.

The Renewable Energy Sources are going to be mainly solar and wind energy, quantifying the energy productions with a simulation software named SAM Energy which will show the performance depending on several key energy parameters. With its results, is calculated the energy production capabilities as well as the economical savings.

Keywords: RES, SAM Energy, solar PV panels, wind turbines.

1 Introduction

1.1 Introduction

Barcelona has experienced a great growth in the recent years. This growth has impacted in different parameters such as population, wealth or energy demand. Specifically, in order to handle this growth with the consequently energy demand increase, Barcelona felt the need to move in other directions different as the current one, which was producing energy from fossil fuels and, due to that, be a high dependant of this source of energy.

In 1995, approximately de 86% of the energy consumed in the city was being supplied from non-renewable resources as oil, coal and natural gas. The use of these resources implies many problems for the environment and its inhabitants. Therefore, it is the new engineer's generation responsibility to investigate those topics so that it can be possible to make actions and decrease as much as possible this percentage of non-renewables sources.

In this project, Barcelona's potential and energy resources are analysed. Between all the renewable energy that can be exploited, the main ones in which this work is focused on are solar and wind energy. Those technologies have been already widely developed in other countries and the knowhow of its operating procedures it is well-known, which is a great advantage when it comes to make a project of these characteristics.

Following the lines of the renewable energy plan for 2020 that Barcelona has proposed, this project proposes several and different energy models based on those two technologies mentioned above, alongside with energy production simulations and economic analysis.

The purpose of the RES plan is to reduce the dependency of the city of fossil fuels from an 86% in 1995 until a 65% for 2020. This will help the city to be a smarter city, cleaner and with a clever perspective when it comes to self-energy production.

As mentioned, within this research it is been studied the behaviour of solar PV systems and wind turbines, altogether with its own capabilities and deficiencies, in order to know and set the boundaries of them and be able to provide a reliable energy model in order to help the government of Barcelona to promote this movement to greener scenarios.

1.1.1 Project Objectives

The main objective of this Master Thesis is to make a high-level picture of the energy system that it is been developed in Barcelona, Spain. This study contains the renewable energy resources available for the city, the economic analysis of a big scale implementation of an energy production system and the matching mix of technologies that can be used in this region based on the resources that are available.

From this general objective, a series of specific objectives can be generated which are listed below:

- Establish a renewable energy resources picture of the city of Barcelona.
- Identify which are the lacks and virtues of the city in terms of energy availability and find out where and which is the potential that can be developed.
- Analyse the initiatives and the funds that the government has destinated for the development of a greener city and reduce the CO_2 emissions.
- Calculate the energy needs for each building in the city, from households to buildings of flats and commercial sites. Moreover, extrapolate this unitary energy needs for the entire city and surroundings (Barcelonès).
- Establish an energy demand profile for the region and cover this demand as much as possible with different technologies.
- Simulate with SAM (System Advisor Model) Energy software which could be the annual energy production and analyse the several outputs that the program can bring out.
- Make several analyses of the different technologies, compare the results (energy obtained, budget for the project, etc.) and choose the best option according to the funds available. Define the horizon of the project and its stages.

Even though the scope of this project is focused on the area of Barcelona, the main aim of it is to make an energy model and a way of analysing regions so that the reader can understand how to make a complete energy analysis of any desired location.

Besides, this work is trying to explain how potential and energy production should be calculated and analysed, which are the parameters that the user needs to consider and how they should be measured.

Finally, this project could be a tool to help governments to go forward on several implementations of renewable energy production systems, saving money, reducing CO_2 emissions and making smarter cities with a higher percentage of energy production coming from renewable resources, helping humanity to go into greener scenarios.

1.1.2 Origin of the project

This project comes out due to a collaboration with the Incheon National University located at the city of Incheon, South Korea. The department where I am working in is the EPSE laboratory where they carry and develop renewable energy solutions that can be applied in real cases.

The main origin of the project is based on the high amount of pollution surrounding the area of Barcelona and how it can be reduced. Besides, a high percentage of energy consumption is coming from non-renewable energy resources which impact on the emissions and, therefore, on the pollution. So basically, the main reason of this project is to make a model of energy production based on renewable technologies in order to reduce pollution and turn Barcelona into a smarter city.

1.1.3 Motivation

Even though my specialization in my Master's degree is *Management in Engineering* I decided to carry out a project based on renewable energies because during the Master I have been in contact with several subjects related to energy and I enjoyed getting introduced to that world and getting to know the background needed.

Besides, I personally think that if I can do something for humanity with all the knowledge acquired during my studies, is take advantage of it and work on changing the world and letting it go forward by focusing the direction on a smarter, cleaner and respectful way of produce energy with all the technologic development we have so far.

1.1.4 Previous requirements

The previous knowledge needed to understand this project is how the technologies, that are going to appear later in this paper, do they work and how are the build, the range of efficiency that each of them have, the losses that can appear during the production, transformation and transport of energy, the capacity of every device needed for the proper operation of the systems, among other basic concepts of energy.

Is needed a basic tutorial as well on how to use *SAM Energy* software. Despite it is a simple software, the user needs to now the significate of every field in order to be able to understand the results that come out from it.

1.2 Glossary

- **PV**: photovoltaic system, also PV system or solar power system, is a power system designed to supply usable solar power by means of photovoltaics. It consists of an arrangement of several components, including solar panels.
- **RES**: Renewable energy (sources) or RES capture their energy from existing flows of energy, from on-going natural processes, such as sunshine, wind, flowing water, biological processes, and geothermal heat flows.
- **DH**: Geothermal District Heating (GeoDH) is the use of geothermal energy (i.e. the energy stored in form of heat below the earth's surface) to heat individual and commercial buildings, as well as for industry, through a distribution network.
- **EGS**: An enhanced geothermal system generates geothermal electricity without the need for natural convective hydrothermal resources.
- **NPV**: Net present value is the difference between the present value of cash inflows and the present value of cash outflows over a period. NPV is used in capital budgeting and investment planning to analyse the profitability of a projected investment or project.
- **CSP**: Concentrated solar power (also called concentrating solar power, concentrated solar thermal, and CSP) systems generate solar power by using mirrors or lenses to concentrate a large area of sunlight onto a small area.
- **TOE**: The tonne of oil equivalent (toe) is a unit of energy defined as the amount of energy released by burning one tonne of crude oil.
- **Azimuth / Tilt angle**: The surface azimuth angle is the angle between south and the horizontal projection of the surface normal. The surface tilt angle is the angle between the surface normal and vertical.
- **GHI**: total irradiance from the sun on a horizontal surface on Earth
- **DHI**: radiation at the Earth's surface from light scattered by the atmosphere
- **DNI**: amount of solar radiation received per unit area by a surface that is always held perpendicular (or normal) to the rays that come in a straight line.
- **Weibull K factor**: The Weibull *k* value, or Weibull shape factor, is a parameter that reflects the breadth of a distribution of wind speeds.
- **Electric and thermal watt (We/Wt):** The term electric watt corresponds to the production of electrical power; the term emphasizes that only power generation power is spoken without the heat that can be generated. The term thermal watt is the unit of thermal power, with this concept we want to emphasize that only the heat generated is spoken of.

2 Preface

2.1 Barcelona general aspects

2.1.1 Location, size and extension

The city of Barcelona is based on the east coast of Spain, it is located on the shore of the Mediterranean Sea, about 120 km south far from the Pyrenees and the border with France, on a small coastal plain bounded by the sea to the east, the *Collserola* mountains to the west, the *Llobregat* river to the south and the *Besós* river to the north. It is the capital of Catalunya, one of the autonomous communities in which the country is organized and split into different regions.

Barcelona has a total extension of 102 km^2 (only the city) but the metropolitan area of Barcelona, which is going to be the area of study of this project, has an extension of 334.6 km^2 with 2,819,867 inhabitants. In the following figures, Figures 1 and 2, it can be shown in a map where exactly is located:

Figure 2. Map of Spain

Figure 1. Map of Barcelonès province

2.1.2 Climate

Barcelona and its metropolitan area have a Mediterranean climate, with mild winters and hot summers. According to several climate classifications, Barcelona has a warm-temperate subtropical climate. As the city is located on the eastern cost of the Spain, Atlantic lows often arrive in Barcelona with low humidity producing little or even no rain. The proximity to the Mediterranean Sea, is the reason why the summers are not as dry as in many other Mediterranean Basin locations.

Average temperatures and precipitations

The “mean daily maximum” (solid red line) shows the maximum temperature of an average day for every month of Barcelona. Likewise, “mean daily minimum” (solid blue line) shows the average minimum temperature. Hot days and cold nights (dashed red and blue lines) show the average of the hottest day and coldest night of each month of the last 30 days [1]. The following figure, Figure 3, shows the yearly evolution of the temperatures of Barcelona.

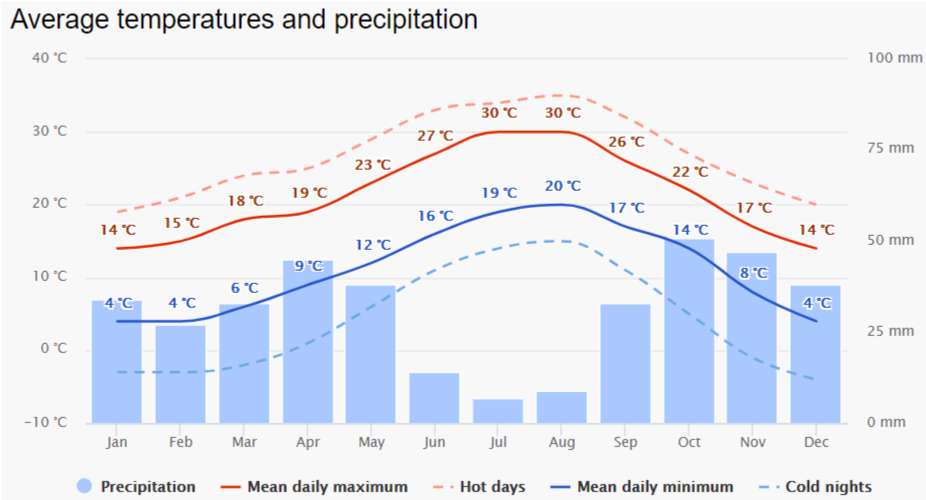
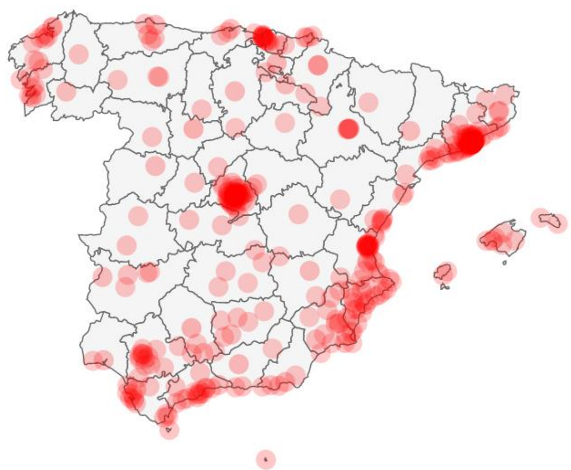


Figure 3. Average temperatures and precipitation of Barcelona

2.1.3 Demography

The population of Spain is 46,440,576. This is a significant figure since the total population back in 1960 was 30.5 million as reported by Eurostat (it becomes a 52% increase over the last half-century [2]. As it can be seen at the Figure 4 below, the population for Barcelona is 1,621,537 inhabitants which represents de 3.5% of the total population of the country.



Name	Population ▾
Madrid	3,255,944
Barcelona	1,621,537
Valencia	814,208
Sevilla	703,206
Zaragoza	674,317
Malaga	568,305
Murcia	436,870
Palma	401,270
Las Palmas de Gran Canaria	381,847
Bilbao	354,860
Alicante	334,757
Cordoba	328,428
Valladolid	317,864
Vigo	297,332
Gijon	277,554

Figure 4. Spain population classified by city

According to the census in 2008, Spain had about 46,157,822 inhabitants and 505,992 square kilometres make up the total surface area of this country. This translated to a population density of about 91.4 people per square kilometre, which is a low density compared with the rest of Western European Countries.

Spain Population Growth

According to a 2012 estimation, the population growth rate of the country is 0.654% pointing to the fact that Spain is set to experience slow but steady population growth over the years.

The population growth rate experienced a drastic rise at the start of the 20th century, as seen on Figure 5, due to a boom in the industrial sectors of Spain and even more so in the 1960s and 1970s.

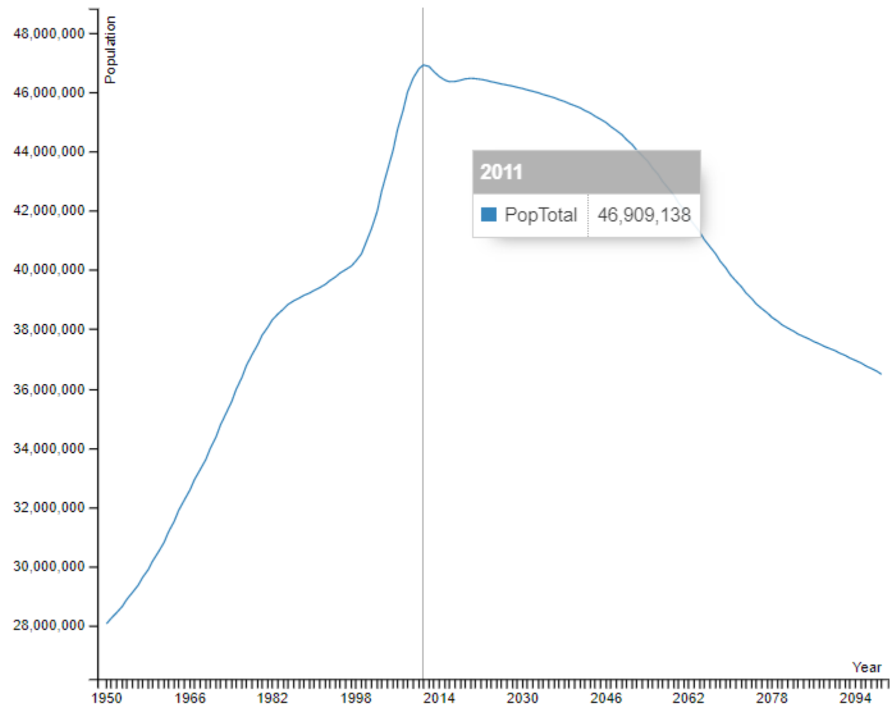


Figure 5. Spain population trend line (1950-2094)

Even though the population of Spain is based on natives, the country's population has increased significantly as a result of migration from Latin America, East Europe, North Africa and sub-Saharan Africa.

During the 20th century, the population of Spain doubled, although the trend was uneven due to large-scale migration from rural areas to urban ones with core industries in the economy.

2.1.4 Emissions

The Spanish country is showing nowadays 5.14 tons of CO2 emissions per capita [3], but it is an interesting and positive point to look at the evolution of the charts, on Figure 6, as it is showing a drop from the year 2005 and still decreasing.

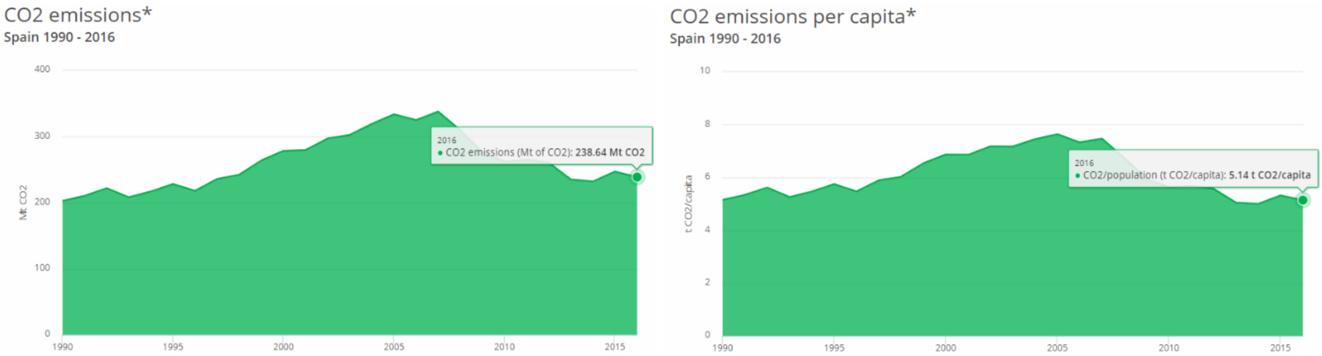


Figure 6. CO_2 emissions (total and per capita)

That means that the country is investing and proposing initiatives in order to keep reducing those harmful emissions (most of the reduction comes from energy production based on renewable resources).

2.2 Barcelona energy system

Based on the results found at *index mundi* website [4] we can see that Spain is located at the 15th position worldwide in terms of energy production with 267.1 billion kWh and in the 16th position in terms of energy consumption with 240.4 billion kWh.

Rank	Country	Electricity - production (billion kWh)
1	China	6,142
2	United States	4,088
3	India	1,289
4	Russia	1,008
5	Japan	976.3
6	Canada	643.2
7	Germany	588.5
8	Brazil	559.2
9	France	536.1
10	Korea, South	528.1
11	Saudi Arabia	318
12	United Kingdom	309.8
13	Mexico	292.7
14	Italy	269.3
15	Spain	267.1
16	Iran	265.1
17	Taiwan	264.1
18	Turkey	245.8
19	Australia	237.9
20	South Africa	229.2

Rank	Country	Electricity - consumption (billion kWh)
1	China	5,920
2	United States	3,911
3	India	1,048
4	Japan	933.6
5	Russia	890.1
6	Canada	516.6
7	Germany	514.6
8	Brazil	500.6
9	Korea, South	497
10	France	436.1
11	United Kingdom	301.6
12	Italy	296
13	Saudi Arabia	292.8
14	Taiwan	255.3
15	Mexico	245.2
16	Spain	240.4
17	Australia	223.6
18	Iran	220.9
19	Turkey	213.2
20	South Africa	207.7

Figure 7. World ranking electricity production and consumption

Despite it is not far in relative terms of ranking position from the first one, which is China basically due to its extension and huge industrialisation, once reviewed the numbers at Figure 7, it can be appreciated that China is producing 23 times more than Spain in terms of billions of kWh.

2.2.1 Energy distribution

Related with the energy distribution regarding the different kinds of primary energy available at the country, we can see at the following Chart 1 the variations on the production and imports during a 20-year horizon:

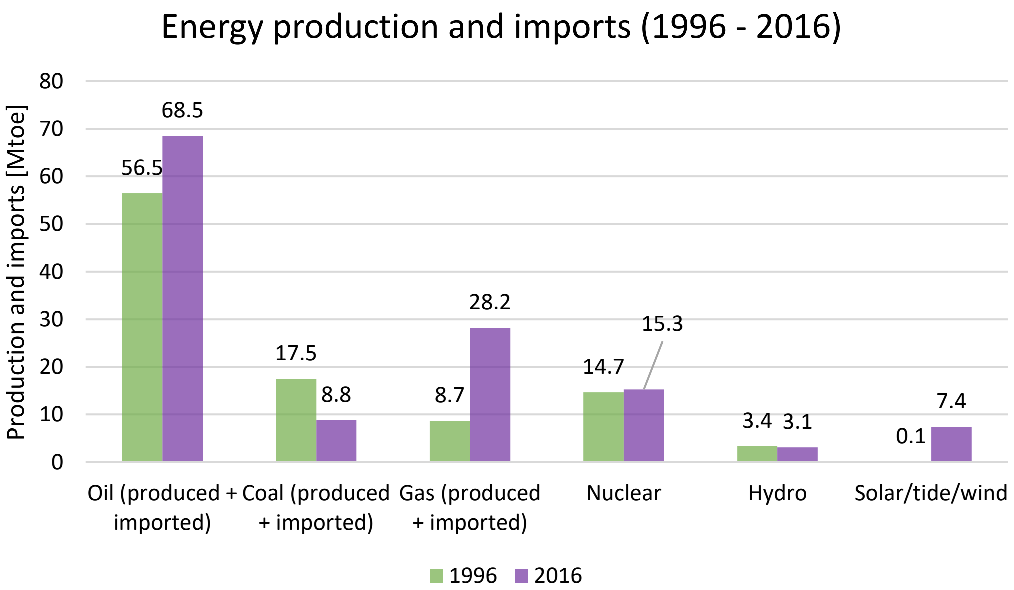


Chart 1. Energy production and imports in Spain (1996-2016)

The energy production regarding oil has increased a 21.2% as well as the one shown regarding gas, which has increased even more, around 3.24 times higher in 2016.

Spain is a country that has experienced a great growth over the past years. This growth has affected the country's demand, which has increased significantly. Moreover, it can be seen when doing the comparison between the two Sankey diagrams [5] that are shown below in Figures 8 and 9. In 1996 the country's total energy demand was 116.1 Mtoe with a final consumption of 69.2 Mtoe.

However, in 2016, after 20 years, the total demand energy was 159.2 Mtoe with a final consumption of 82.2 Mtoe. The total energy demand has increased almost a 40% during this period.

It should be highlighted the increase of the renewable energies as well (Solar, Tide and Wind), which has been evolved from 0.1 Mtoe at 1996 until 7.4 Mtoe at 2016, which means that the country it has been putting efforts on changing the way they produce energy and betting for renewable resources.

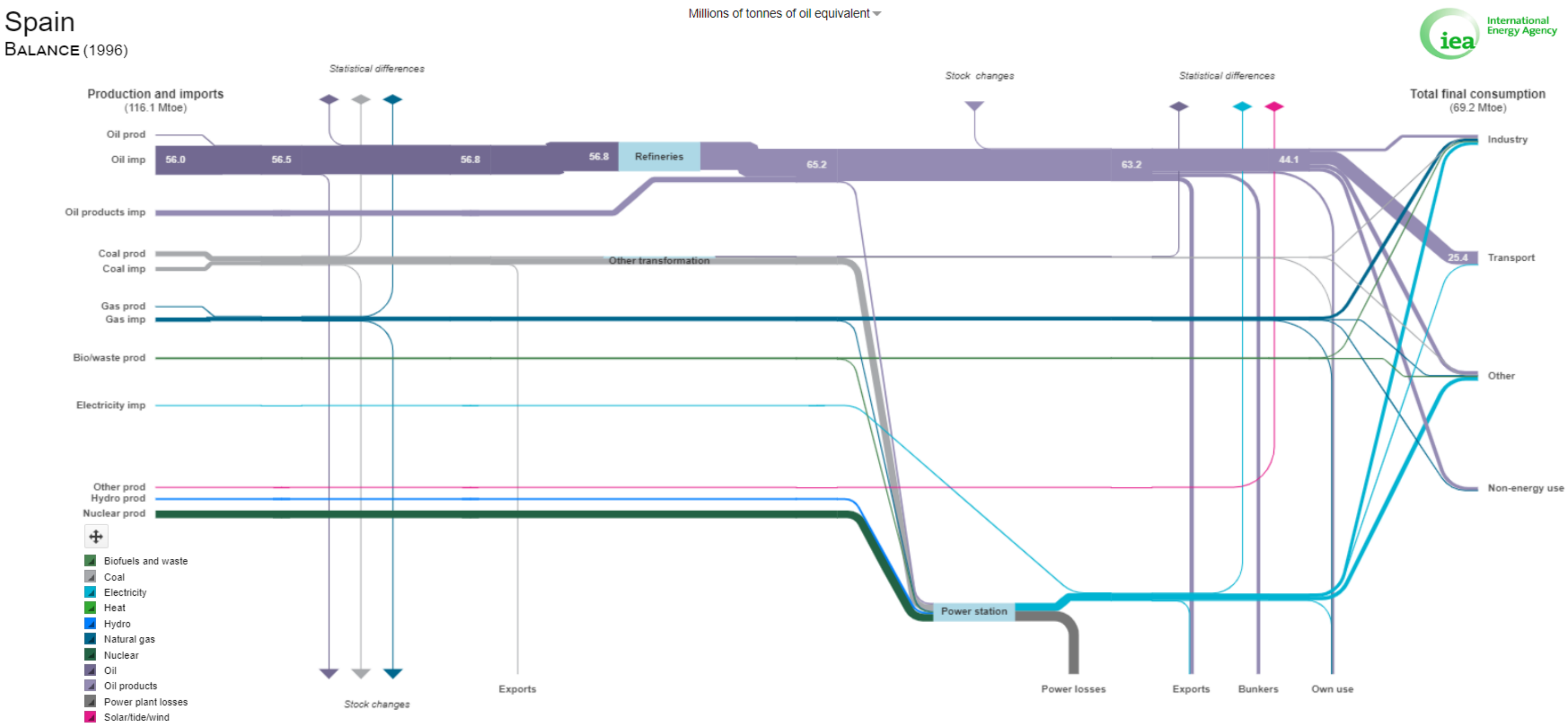


Figure 8. Spain Sankey diagram in 1996

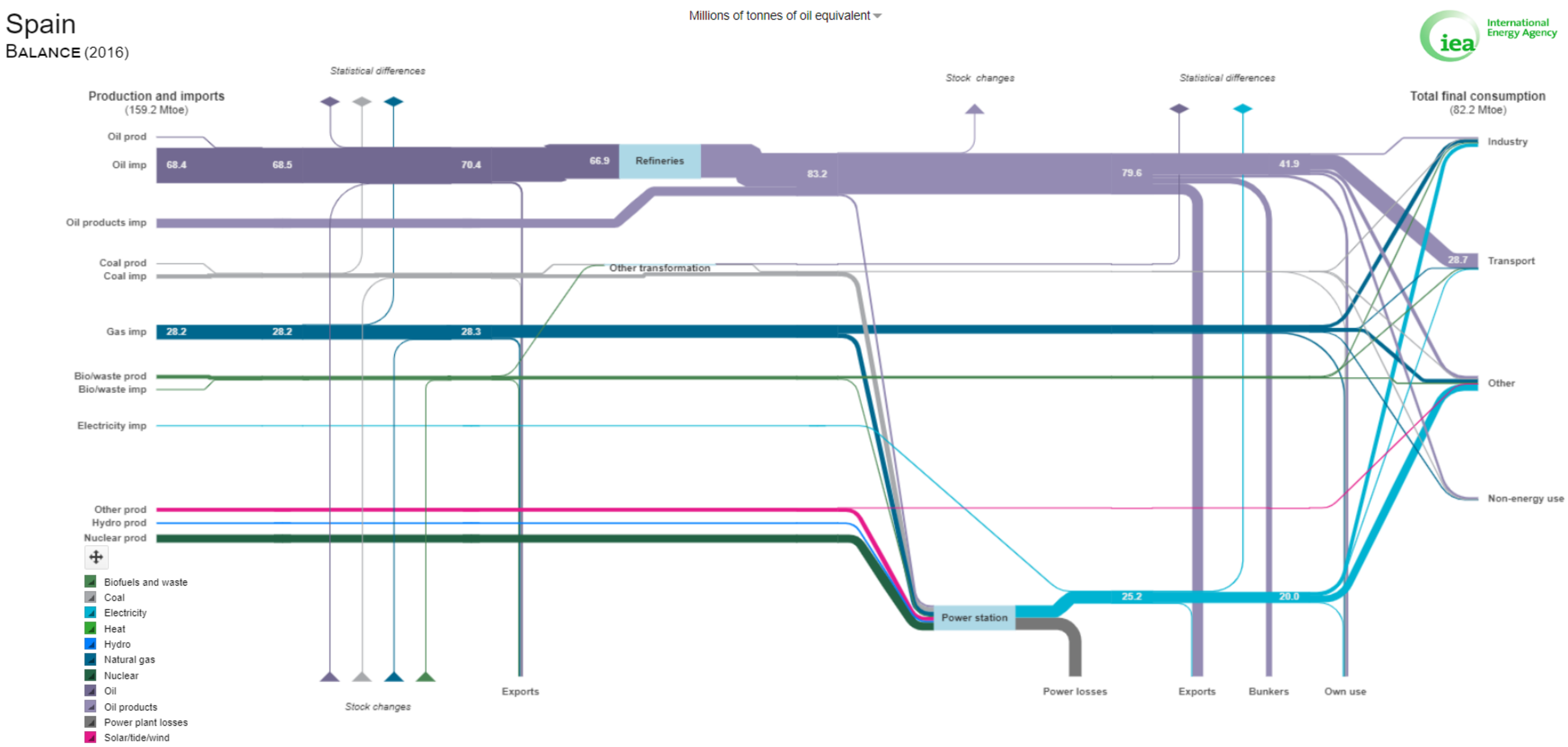


Figure 9. Spain Sankey diagram in 2016

Primary energy distribution

As the figures show below, the energy coming from most of the non-renewable resources has been decreased due to the development and progress of renewable technologies. So, if we sum up Nuclear, Coal and primary and secondary Oil, in 1995 the percentage of all those three technologies was around 86% which is letting us know that most of the energy was coming from non-renewable resources, but if we take a look to 2015 those three energies have dropped until a 65% of the total energy distribution around the country [6].

Moreover, it is important to highlight that energy coming from geothermal and solar resources have increased from 0% until 6%, as well as Biofuels and waste which has increased its share in a 2%, while Hydro has maintained its percentage, as shown on Charts 1 and 2.

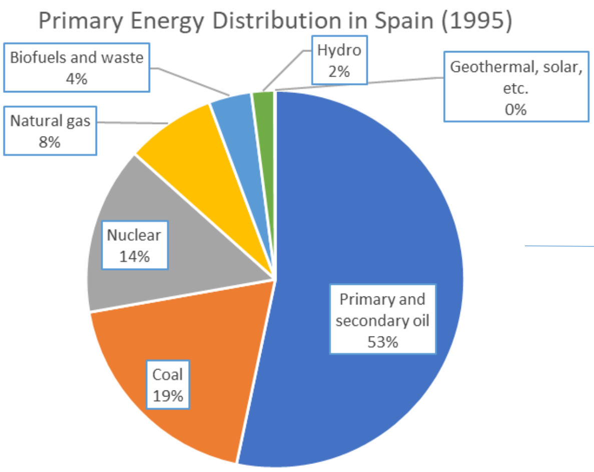


Chart 3. Primary energy distribution in 1995

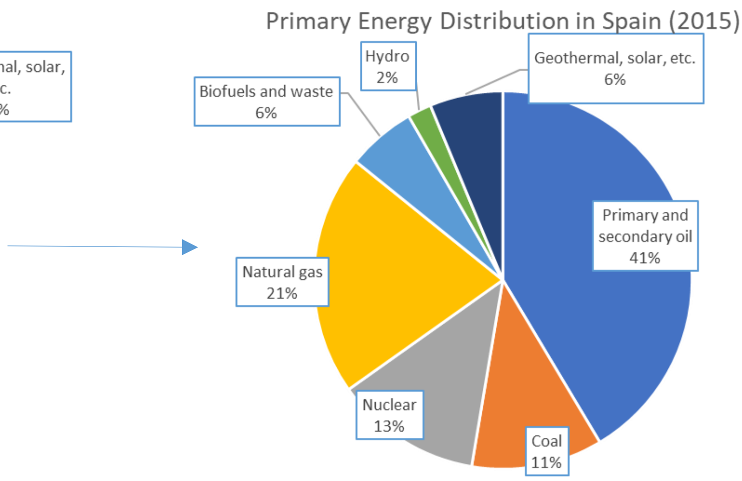


Chart 3. Primary energy distribution in 2015

Now that it can be shown a fair picture of the energy system in Spain, it should be needed to show which is the performance in Barcelona, as this project is going to be more focused in this area and it is necessary to know how it was and how it is going to be the paradigm related to the energy system of the city.

Following the *Pla de l'Energia i Canvi Climàtic de Catalunya 2012-2020* [6], shared by the government of Catalunya, the region where Barcelona is located inside the Spanish country, we could be able to have an idea which is exactly the energy picture, and which are the initiatives or investments that the city is taking.

The Figure 10 below shows how the energy produced from renewable resources has been evolving (and it is expected to evolve) from 2009 until 2020:

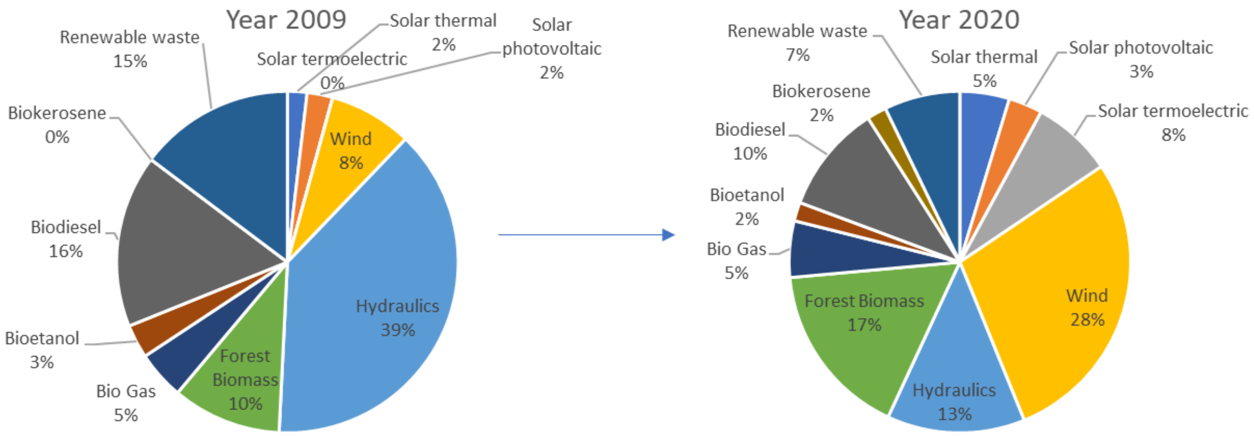


Figure 10. Renewable energy technologies evolution (2009-2020)

So, as it can be seen in the pie charts above, the government of Barcelona is taking actions in order to increase the percentage of renewables. A clear example of it is the increase of wind energy which comes from an 8% in 2009 until an expected 28% in 2020.

Even though the city of Barcelona is not a windy city because of its lack of wind speed, the government is betting for small-scale wind farms or even small turbines installed in residential and commercial buildings.

Regarding the energy coming from the sun, it is planned to increase in all the technologies available (solar thermoelectric, solar thermal and solar photovoltaic). Actually, and due to high degree of hours of sun in the Spanish country, solar energy is a technology which it is being rising over the last years.

In order to sum up all the information above, the following table is showing the results in numbers (expressed in kWh/year):

Technology	Year 2009	Year 2020
Solar thermal	213,992.00	2,072,466.00
Solar photovoltaic	280,283.00	1,416,534.00
Solar thermoelectric	-	3,376,189.00
Wind	912,955.00	12,498,761.00
Hydraulics	4,460,105.00	5,769,643.00
Forest Biomass	1,195,564.00	7,348,997.00
Bio Gas	529,165.00	2,363,216.00
Bioethanol	368,671.00	781,536.00
Biodiesel	1,891,038.00	4,547,330.00
Biokerosene	-	817,589.00
Renewable waste	1,702,632.00	3,170,338.00
Total Renewables	**11,554,405.00**	**44,162,599.00**

Table 1. Energy production by renewable technology (2009-2020)

According to the climate change plan that it has been published, he government of Barcelona has destinated a global investment of 26,400 M€ in terms of renewable energy projects.

From that amount, 10,433.3 M€ are destinated to a renewable energy plan (in one hand, 8,433.4 M€ to electric energy production in special regime and isolated PV, and in the other hand, 1989.9 M€ to thermal solar energy and biomass production). Besides, it has been destinated 9,091.3 M€ to an Energy Efficiency Savings Plan, 5,709 M€ for an Energy Infrastructure Plan and 1,153.5 M€ to produce electricity in ordinary regime.

Moreover, in terms of wind energy is going to be invested the amount of 5,093 M€, so that means that the Catalan government is betting in this technology for the future to be developed, 1,507.2 M€ for solar thermoelectric technology and 1,176.7 M€ for solar photovoltaic. Finally, it is expected that the end user of this energy around the city of Barcelona are going to be investing 7,997.9 M€ which are subdivided into 2,907.9 for the domestic sector, 2,221.2 M€ destinated to services and 2,000.3 M€ for the industrial sector.

After all these investments and initiatives mentioned before, the picture expected for the evolution of renewable energy in Barcelona is shown on the following Chart 4:

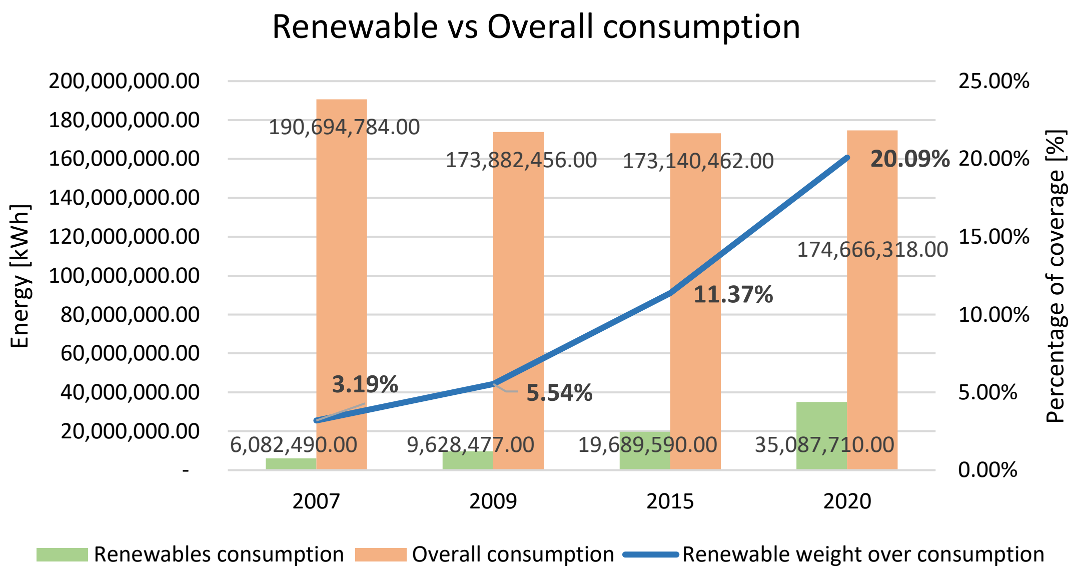


Chart 4. Renewable vs. Overall consumption trend (2007-2020). Own elaboration.

Clearly it can be seen that consumption based on RES is going to increase as it is easy to see at the chart above that the city is going to evolve from a 5.54% of renewables consumption in 2009 until almost a 21% in 2020 which turns in a good trend if we relate it to the past years [6].

Later in this work it will be shown, alongside with the demand profile of the city, which can be the percentage of energy that can be covered with RES, considering the economic side at the same time. The obvious consequences after all those moves are the ones which the government was looking for, which is the reduction on the CO_2 emissions. The evolution of this reduction can be appreciated at the figure below:

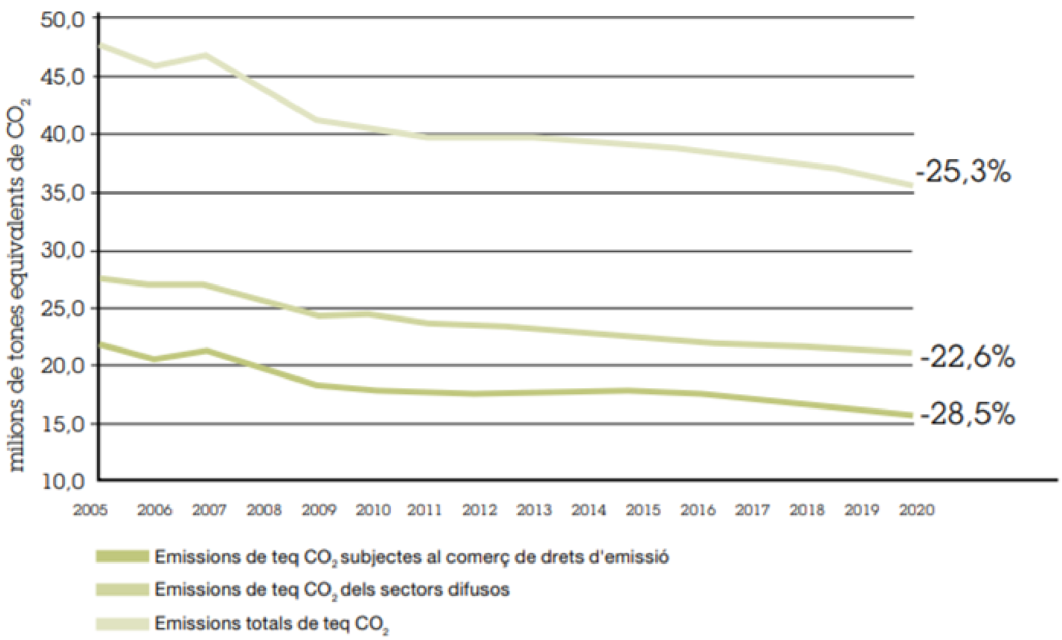


Figure 11. CO2 emissions decrease trend in Barcelona (2005-2020)

As it is shown in the graph above, the total emissions in equivalent tones of CO_2 have decreased from approximately 48% until roughly a 35% what it turns in a 25.3% drop.

The government of Barcelona is taking some other actions, like promoting the public and electric transportation or preventing cars to circulate by the street of the city in some specific days, in order to reduce the levels of pollution and the CO_2 emissions.

So, all this actions that are being taken, are focused towards turn Barcelona in a cleaner and green city.

2.2.2 Energy sources

2.2.2.1 Non-renewable energy sources

At the previous analysis that has been carried out at the primary energy distribution charts, it is possible to see that the Spanish country is highly dependent on non-renewable energy sources such as coal, natural gas, oil and nuclear energy (still in 2015 an 86% of the primary energy it is being supplied by non-renewable sources).

According to the graph extracted from the International Energy Agency Atlas of Energy (Figure 12, the one on the left), in 2015 the self-sufficiency of Spain was around 27% which means that within the whole country, only that percentage of energy it is being self-provided and supplied by renewable sources [7]. Even though, there is lot of room for improvement at the self-sufficiency of Spain, from 2015 until now the trend is positive and is continuously increasing. That is due to the momentum of creating initiatives that the government are carrying out and, for the future, it is expected that this is going to get better.

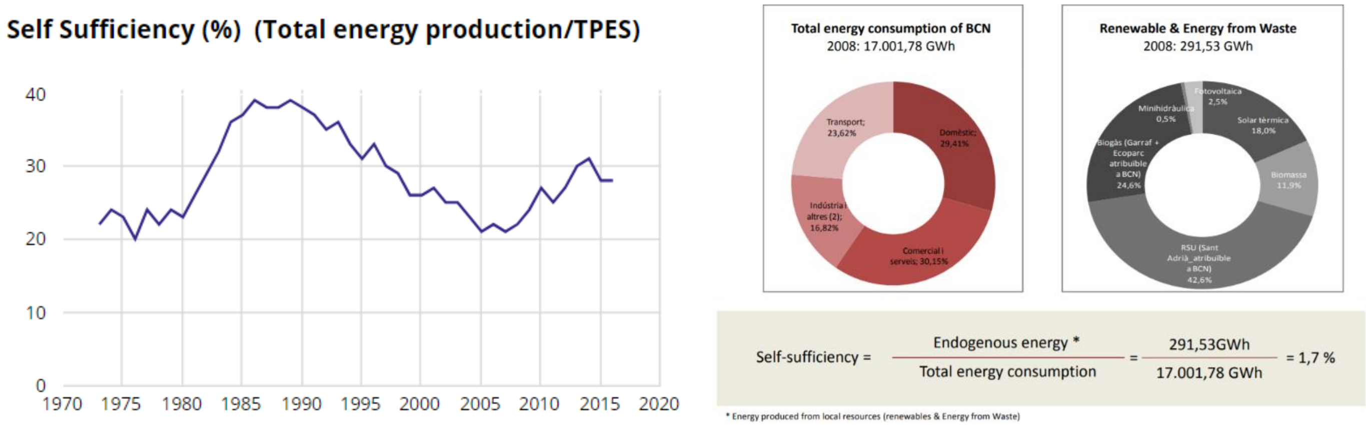


Figure 12. Self-sufficiency trend in Spain (left) and in Barcelona (right)

Despite this, at the Figure 12, on the right, it can be appreciated that the self-sufficiency of the city of Barcelona is not that high compared with the Spanish one [8]. Actually, only 291.53 GWh/year out of 17,001.78 GWh/year can be provided from renewable energy sources which leads Barcelona to have only a 1.7% of self-sufficiency.

So that, this is the reason why the government of the Catalan city is investigating on which could be the alternatives or the main actions that could be taken in order to improve this metric.

2.2.2.2 Renewable energy sources

As is has been demonstrated in the previous points, Barcelona is not currently making that much use of its own renewable energy resources. However, this does not mean it does not have. In the following section it is going to be analysed all the renewable energy sources of Barcelona and check whether they have potential or not, or even which are the initiatives that the government is taking in order to exploit these technologies.

Solar energy

As it can be seen at the figure 13 below, there is a yearly average of 9.03 sunny days and 15.83 partly cloudy days. Even though the partly cloudy days are less sunny than the sunny ones, they can still be counted as days that solar energy can be used and taken profit from.

So that means that, counting the partly cloudy days too, the probabilities of using solar energy increase significantly as considering both categories turn out to be an 83% percentage of sunny days [1] that the solar systems can be working and transforming and supplying energy from the sun each month.

Taking into consideration that the partly cloudy days are not as effective as the sunny days are and applying a 40% reduction of efficiency at the partly cloudy days, it turns that the sun could provide energy the 62% of the days every month, which leads to think that solar energy is a good renewable resource for the city, in terms of availability and efficiency.

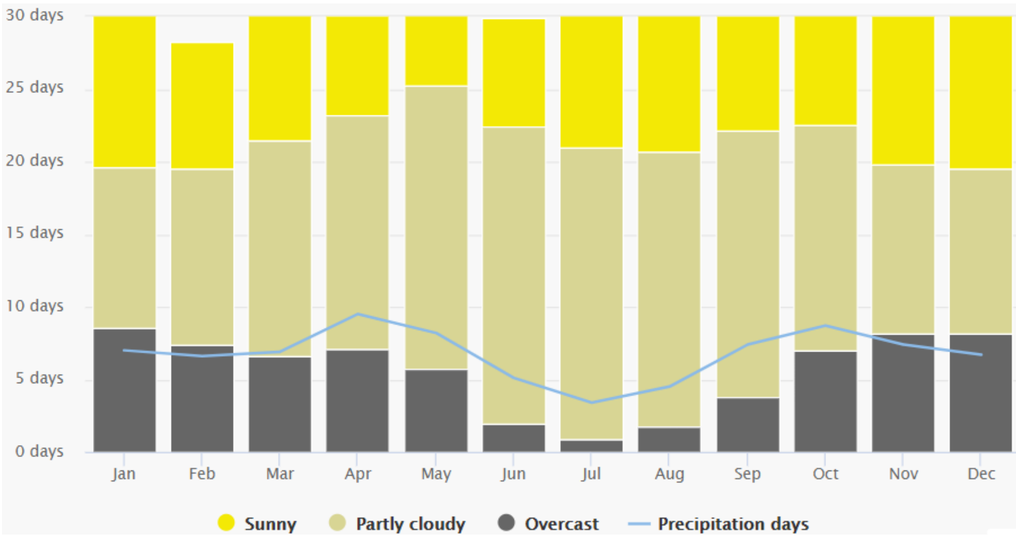


Figure 13. Detailed sunny and partly cloudy days per month and average precipitation days in Barcelona

It is also fair to comment that the implementation of a solar system cannot rely completely on the data provided before as solar energy is unstable and it is not possible to be dependent on the numbers shown above but gives an idea of how much energy could be produced from this renewable source.

Besides, the government of Barcelona has developed an interesting tool [9] which shows the potential of solar production with photovoltaic and solar thermal systems. The map below in Figure 14 is trying to show the future picture of the city in terms of availability of energy potential if all the residential houses would be able to install solar systems at each rooftop.

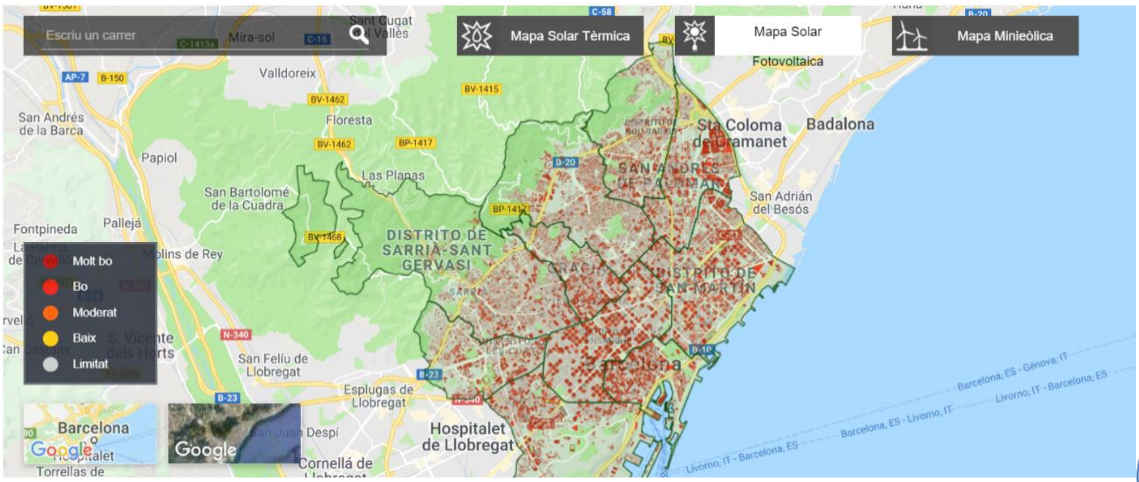


Figure 14. Solar PV potential map in Barcelona

As It can be seen at the map in Figure 15, the map is drawing the city of Barcelona (powered by Google Maps) with the detailed picture of every building and each potential. At the pictures below it can be appreciated which are the results that the map is showing:

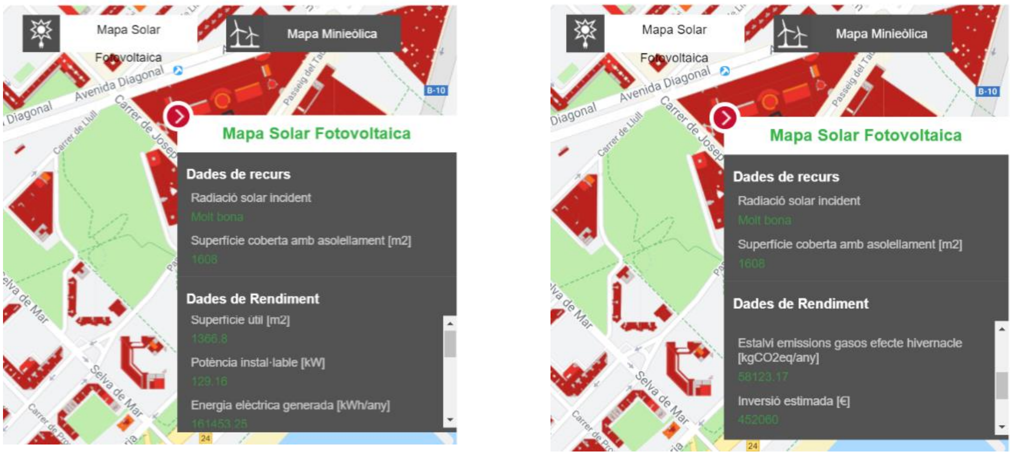


Figure 15. Zoom in with detailed information of the Solar PV map

Making a zoom in at the interactive map and clicking in one of the rooftops of a building, just to give an example, the map shows results such as (on the left side) *available area [m^2]* of the rooftop in order to build the solar panels, the *power installable [kW]* and the *electric energy generated [kWh/year]* that could be provided from this solar system in this building in particular. At the picture on the right side, scrolling down the bar, it can be seen *greenhouse gas emissions savings [kgCO$_2$eq/year]* as well, and the *estimated investment [€]* needed in case of carrying out this project.

Making a zoom out and, in order to know what the potential for the whole city of Barcelona would be [10] if all the buildings shown at the map would install a photovoltaic solar system, turns out that it could be generated a total of **2,505 GWh/year**. At the Table 2 below it can be seen the production depending on the suitability and the area available:

Suitability	PV Module Area [m^2]	No. of buildings	Energy generation [kWh/yr]
	> 20 m^2		
High	2,648,477	30,777	558,444,687
Medium	1,575,238	10,970	296,863,181
	> 50 m^2		
High	1,905,196	10,641	401,314,890
Medium	1,299,003	4,620	245,801,575
	> 100 m^2		
High	1,415,741	4,435	297,969,341
Medium	1,072,364	2,334	203,462,162
	> 250 m^2		
High	876,095	1,244	184,167,561
Medium	676,948	777	129,040,759
	> 500 m^2		
High	559,478	419	117,535,934
Medium	366,789	225	70,441,056
Total High			**1,559,432,413**
Total Medium			**945,608,733**
Total [kWh/yr]			**2,505,041,146**
Total [GWh/yr]			**2,505.04**

Table 2. Solar PV energy production depending on the availability and suitability

Similarly, there is a map for solar thermal energy, providing the same information as in the photovoltaic case. The map is shown below at the Figure 16:

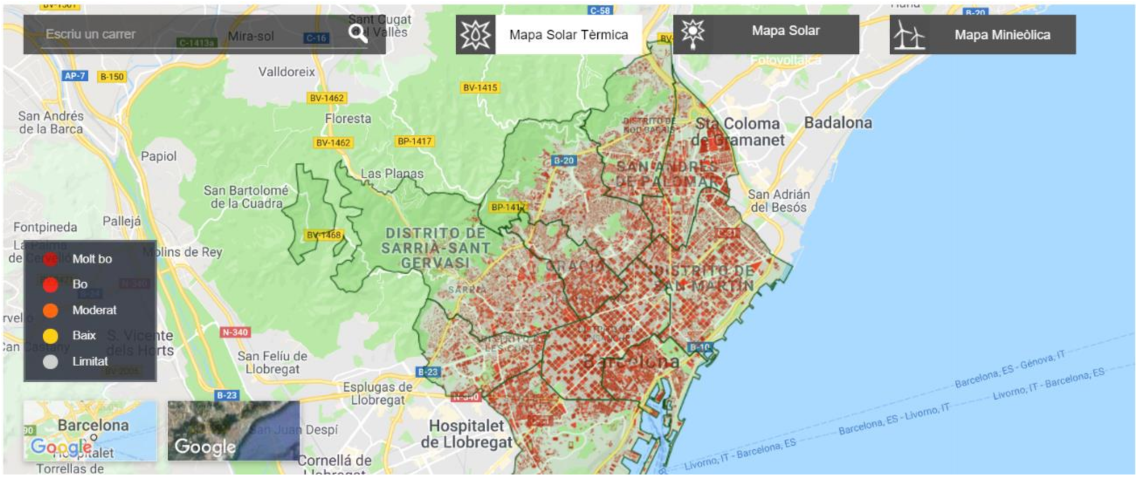


Figure 16. Solar thermal potential map in Barcelona

As shown at the previous case, it is shown the building where would be suitable to build a solar thermal system and how much would be the energy that could be produced and supplied to the buildings. The Table 3 below shows the summary of the results shown at the map:

Suitability	Module Area [m^2]	No. of buildings	Energy generation [kWh/yr]
	> 20 m^2		
High	3,919,864	37,744	3,009,291,956
Medium	1,697,961	15,064	997,883,078
	> 50 m^2		
High	2,989,809	14,034	2,286,821,899
Medium	1,286,505	5,448	754,706,275
	> 100 m^2		
High	2,325,576	6,201	1,774,308,740
Medium	998,905	2,534	584,310,440
	> 250 m^2		
High	1,467,368	1,832	1,118,665,258
Medium	600,969	801	352,661,210
	> 500 m^2		
High	899,110	597	687,257,926
Medium	307,947	223	179,932,202
Total High			**8,876,345,779**
Total Medium			**2,869,493,205**
Total [kWh/yr]			**11,745,838,984**
Total [GWh/yr]			**11,745.84**

Table 3. Solar thermal energy production depending on the availability and suitability

As shown previously at the pie charts that show how the renewable will evolve until the year 2020, we can see a huge potential in the solar thermal resource at it could produce an amount of **11,745 GWh/year** in terms of thermic energy.

All this numbers are considered summing all the possibilities (all the suitabilities independently if they are high or medium) and shown as a potential, not as a real fact.

All this numbers are subject to some considerations and assumptions that can be checked at the Barcelona's government website [10].

So, summing up, this map gives an idea, both to the engineers working for energy companies or either to non-professional users that may want to install a solar system at their own place, what would be the energy potential as well as the investment needed and the energy that these systems could provide.

Wind energy

Another suitable renewable resource for Barcelona would be the energy coming from the wind. Even though this resource does not give too much expectances as the picture below shows the wind speeds for every month and it is not that high, it will be explained later which are the projects that would be suitable for the city of Barcelona.

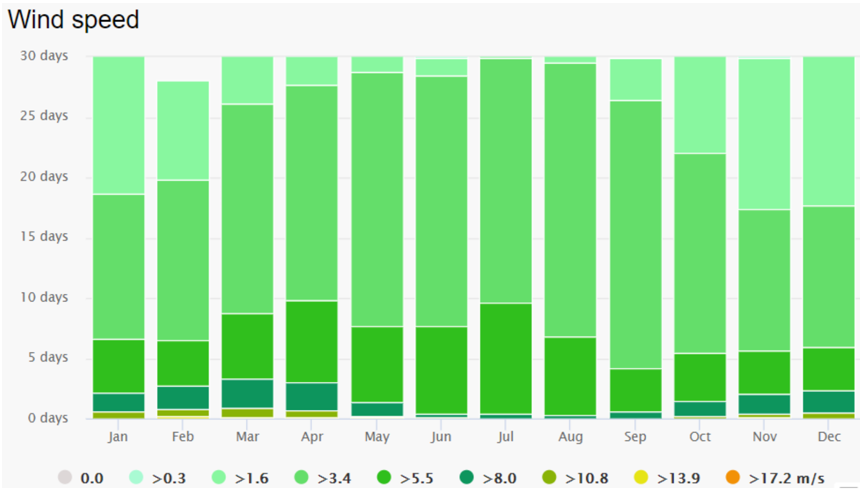


Figure 17. Wind speed ranges distribution per month

At the Table 4 below are shown the summary results for every month and for every range of speed and as mentioned before the numbers are not too much encouraging as the average speed for the city is around 3.5 – 4 m/s. As it will be shown later at this work, the turbines start to work at 2.5 m/s so that will lead to think that with this low available wind speed, the power generated will not be that high.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dic
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	1.98	1.48	0.79	0.40	0.39	0.25	0.18	0.24	0.59	1.44	2.08	2.14
12	4.65	5.68	6.74	7.14	8.10	8.28	7.86	8.79	8.91	6.45	4.72	4.58
19	2.76	2.57	3.31	4.29	3.85	4.62	5.64	3.98	2.29	2.40	2.28	2.21
28	1.35	1.89	2.17	2.14	1.08	0.28	0.36	0.27	0.56	1.18	1.49	1.63
38	0.74	0.81	0.98	0.76	0.12	0.13	0.00	0.00	0.00	0.25	0.38	0.61
50	0.00	0.36	0.16	0.17	0.16	0.00	0.00	0.00	0.00	0.00	0.17	0.00
61	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total [km/h]	11.48	12.79	14.15	14.89	13.70	13.56	14.04	13.28	12.34	11.71	11.13	11.18
Total [m/s]	3.19	3.55	3.93	4.14	3.81	3.77	3.90	3.69	3.43	3.25	3.09	3.10

Table 4. Transcription of the results shown on Figure 17 and monthly averages in km/h and m/s

However, even though this average speed would not be suitable for large wind turbines, the government of Barcelona has generated a wind map that shows the potential of wind energy based on small-scale wind turbines, assuming the installation of 1 kW wind turbines.

Like the solar maps, on the Figure 18 below it can be seen the wind potential that the city would have based on the installation of these small wind turbines at all the spaces available at the buildings around the place.

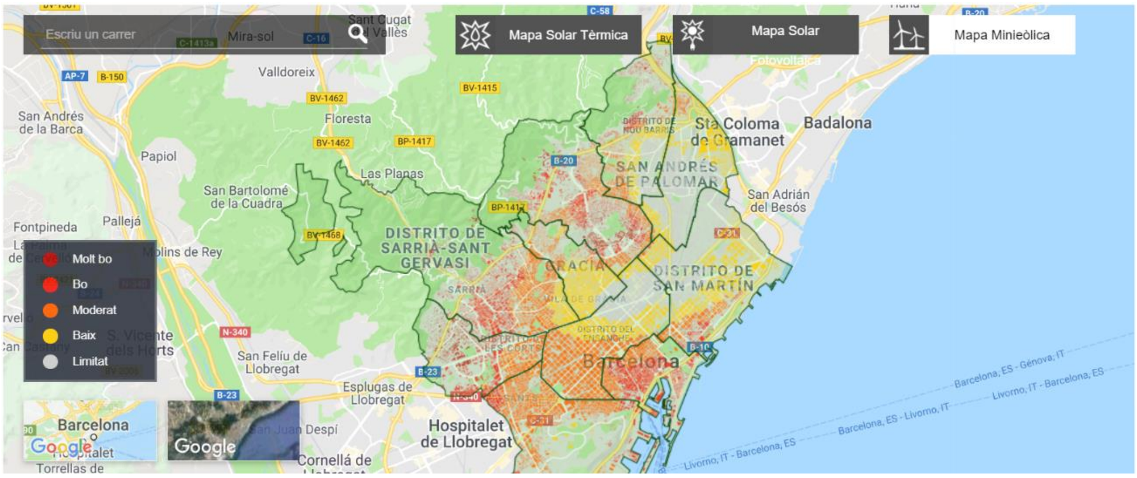


Figure 18. Wind energy potential map in Barcelona

As it can be appreciated, in this case there is less red colour (high-medium suitability) and more yellow one (low suitability) and even there are some spaces with grey colour (limited suitability) which gives the chance to know that the wind implementation will be lower compared with the solar one mentioned before.

In order to sum up, taking into consideration the assumption that in Barcelona there are in between 7,000 and 8,000 hours of suitable wind for producing energy per year, the city would be able to produce **144,000 kWh/year**. If it is been compared this amount with the solar one, it can be seen clearly that the difference is huge, so that leads to think that wind can help in the energy production, but the main renewable resource will be solar energy.

Biomass energy

Another profitable renewable resource would be the energy coming from burning biomass feedstocks. Currently the main sources of this raw input for producing energy in Barcelona is, on one hand, coming from the waste of industry, as the city is fully industrialised at its surroundings and, on the other hand, from the waste of forests as there are large areas of forests around the metropolitan area that can produce this waste and, thus, this can be used to produce energy.

As it will be seen later, it is a resource which availability is high but the efficiency when it comes to energy production is not that high as the systems are expensive and it is needed such a large amount of biomass in order to supply all the energy demand of the city.

In order to set the picture of biomass in Barcelona, first is needed to show how this resource it is been exploited around the Spanish country. At the Figure 19 below it can be seen all the biomass plants that are currently working at the country and classified by power production [11].

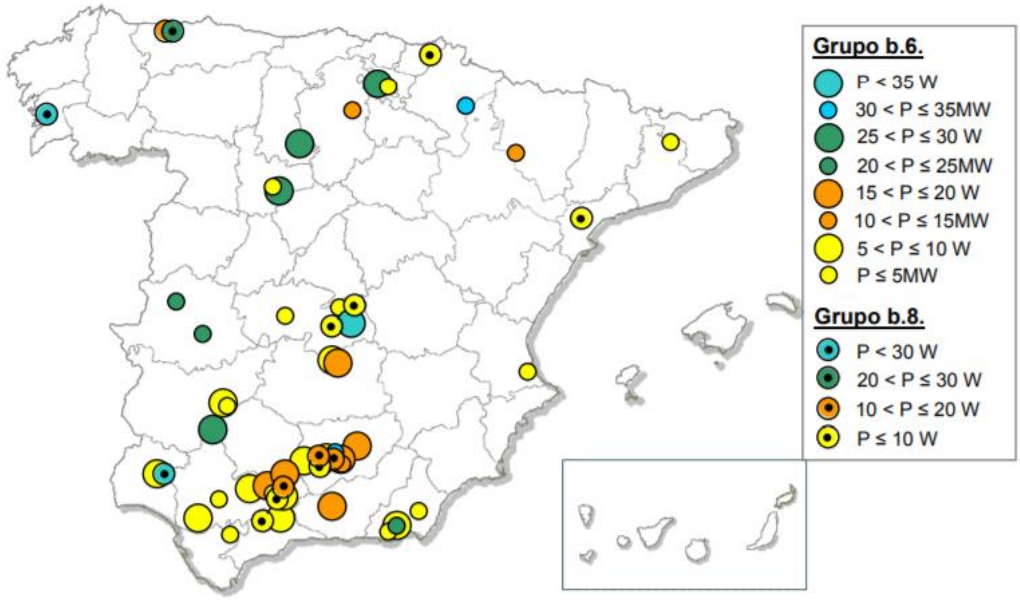


Figure 19. Biomass plants at the Spanish territory

As shown, the main area of exploitation of this resource it is located at the south of the Iberian Peninsula, where agriculture and forests works are the main activities in this area. Looking to Catalunya, the region where Barcelona is located, it cannot be seen too much activity when it comes to biomass energy production.

But deep diving a bit more, it is possible to do a zoom in at the Catalan region and be able to find in Figure 20 several biomass plants currently running and others that are still in construction and that are going to be running in the future.

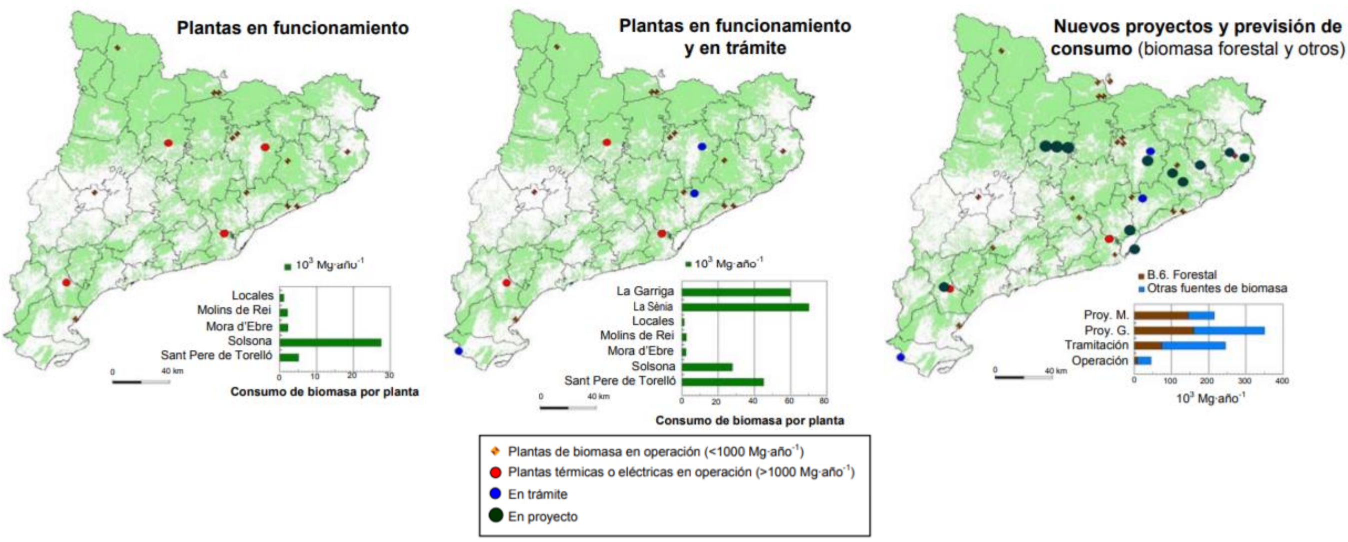


Figure 20. Biomass plants currently running (left), still in construction (centre) and future projects (right) in Catalunya

As shown at the pictures above, there are several projects to build new biomass plants in order to move from and old-fashioned way of producing energy to a new and cleaner way to do it, as the government of Spain is investing in these renewable technologies in order to increase the self-sufficiency when it comes to energy.

Continuing with the zoom in and focusing the attention only at the city of Barcelona it is possible to find the zone classification in terms of biomass resources potential. As shown on the Figure 21 below, the map is showing the potential, not the current activity of biomass exploitation.

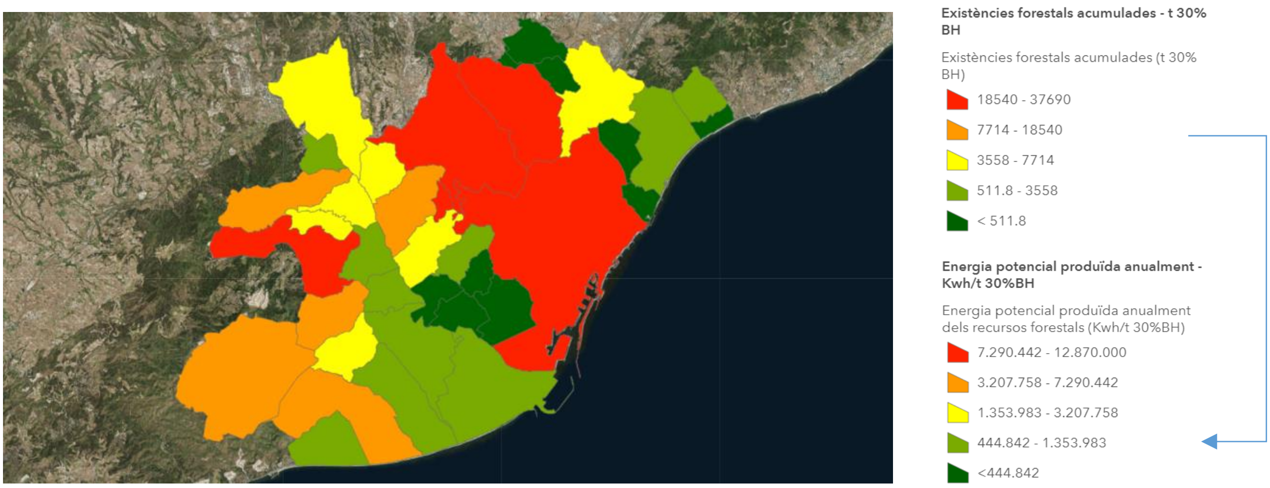


Figure 21. Barcelona's biomass potential map (forest stocks)

In order to put some numbers here, summing all the different zones of the city it turns out that it has around 297,927 tones 30% wet based (with a 30% of humidity in the waste) available that can be used to produce energy [12]. If the city could use all this energy the result would be around 90.73 GWh/year which is far from matching with the whole city energy demand as it will be shown later on this work, but it is an option to take into consideration.

Geothermal energy

Total installed capacity from geothermal sources amounts to 60 GWth worldwide and roughly 20 GWth (1.85 GWe) in Europe, with Germany, Italy, and Sweden as the countries with the highest geothermal capacity installed in the EU-28 [13]. Even though the generation from geothermal energy has steadily grown in the EU-28 for the last 10 years, its total net production barely amounts a 0.2% (it is expected that it will reach 0.3% by 2020).

Although the geologic potential is very large in Europe (see Figure 22) and in the rest of the world (in fact, current electricity demand would be exceeded if all of it were used), the truth is that only a small portion of it can be profitable exploited.

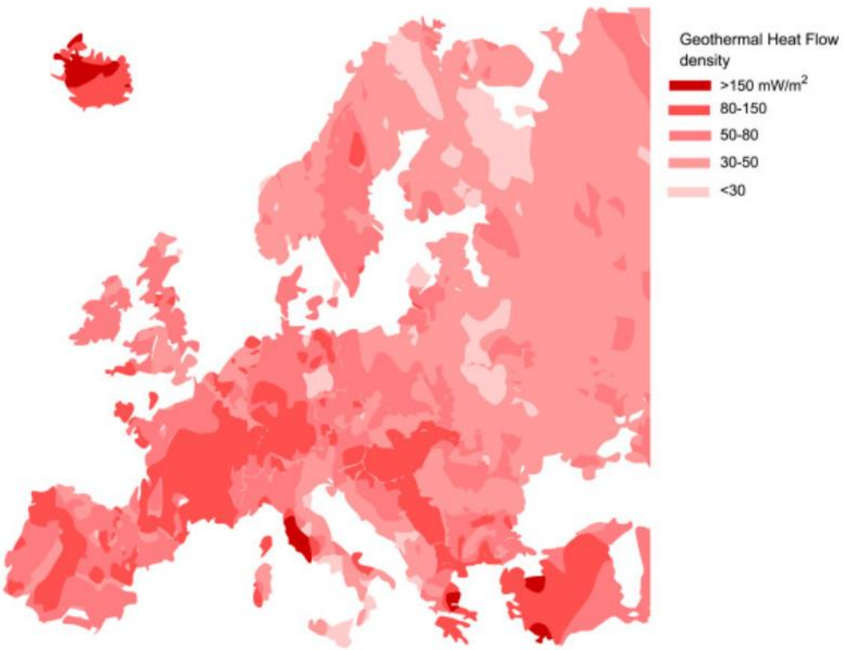


Figure 22. Geothermal Heat Flow density around Europe

The geothermal energy contribution in Spain in 2012 was barely 0.06% of the total installed capacity of power generation (108 GWe) [14]. Besides the pioneering European geothermal regions, the central region of Spain is being given much attention at a pan-European level and is considered to be a promising region for “new developments”.

As is well known, geothermal energy has some important advantages for energy supply due to 24/7 plant operations year round, but each geothermal location requires a prior analysis to determine its fluid and reservoir characteristics, chemical crystallizations and reinjection policy in order to avoid losses in the temperature profile or a reduction of the capacity factor (ratio of hours of plant operation with respect to the total yearly hours), which affects the financial and operational costs.

The geothermal resource is not easily attainable and is needed to perform the conversion into a type of directly usable energy, applying drilling procedures to extract from affordable underground reservoirs hot water, steam or both fluids (defined as energy transportation vectors) placed at depths of 0.2 – 3.2 km in the Spanish territory.

Following the European targets, the Spanish Administration has created the Renewable Energy Plan 2011 – 2020, with a geothermal energy goal of 50 MWe for electricity generation and 66 MWt for direct heating use (12.5 MWt intended to be used in direct-heat purposes and 53.5 MWt to be used with geothermal heat pumps).

The current geothermal situation and distribution are shown in the figure XX, resulting in a low-medium enthalpy resources potential of 610 GWt [15][16].

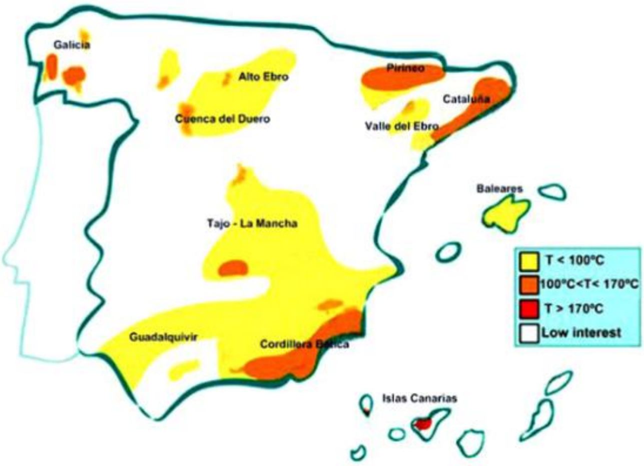


Figure 23. Geothermal distribution (ground temperature) in Spain

Besides that, no additional installations have been performed from 2011, and, currently there are no geothermal plants in Spain associated with DH networks nor generating electricity. Only in the Canary Islands may it be technically feasible to use EGS technology, which is considered to be the most challenging issue facing the geothermal energy sector – it can supply superheated steam as an energy transportation vector that can be transformed directly into electricity [17]

Geothermal energy resource, as explained before, it is an interesting font of energy that can be exploited, and it has been analysed that in the Spanish country there can be some opportunities in order to supply energy from this technology. However, in this work it is not going to be further studied but it can be a future line of research.

Hydro energy

Nowadays in Spain there are 18.8 GW (2.26 GW in Catalunya) of installed power and can produce 37.61 TWh/yr (4.59 TWh/yr in Catalunya) from hydro energy resource [18].

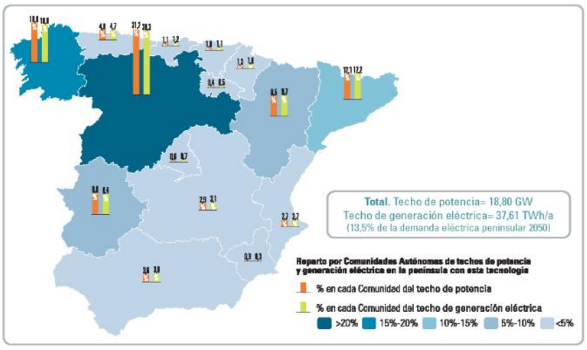


Figure 24. Hydro energy installed capacity and energy generated

Despite it is a technology that has a great potential in Spain, as seen on Figure 24, is not going to be further analysed in this work and would be a future line for research.

Electricity generation and electricity capacity

Following the *Renewable Electricity Capacity and Generation Statistics* [19] from the International Renewable Energy Agency (IRENA) it is possible to picture the electricity capacity and generation of every country, depending on the technology used and the year selected.

For that, IRENA has developed an interesting statistic tool (Figure 25) which the user can acknowledge the electricity situation of the country selected. The tool shows a dashboard with multiple selectable choices as shown at the following figure.

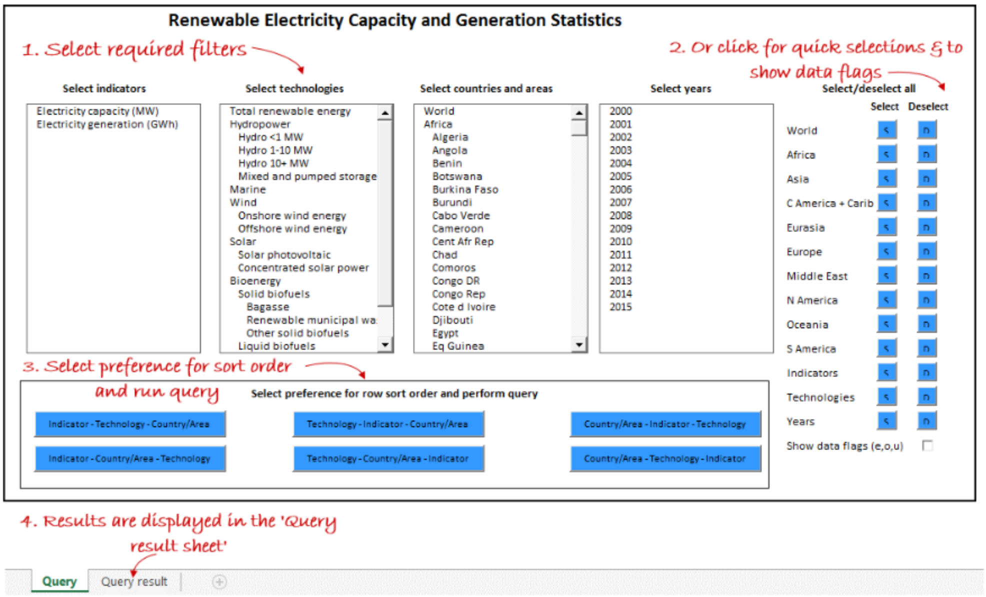


Figure 25. Dashboard view of the tool developed by IRENA

So that, with a simple procedure it is possible to know the capacity and the generation of electricity and it is possible as well to create trend-line charts to see the evolution through the past years.

Accordingly, making use of the tool provided, it has been analysed the electricity generation and capacity of Spain:

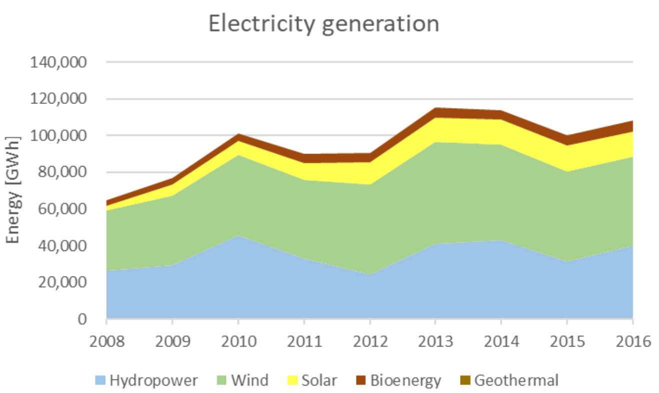


Figure 27. Electricity generation of Spain

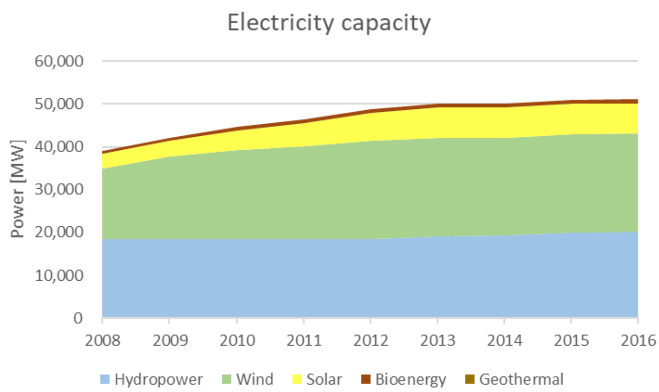


Figure 26. Electricity capacity of Spain

As it can be seen on the figures 26 and 27 in the case of generation it is possible to appreciate several increases and drops during the years but with a positive and increasing trend line, moving from 64,923 GWh of energy production in 2008 until 108,109 GWh in 2016 (66.5% growth rate), which means that the country is moving towards a more renewable way of producing energy and that would explain all the political moves that the Spanish government is working on.

The same happens for the electricity capacity, which has been increasing starting from 39,069 MW in 2008 until the amount of 51,108 MW in 2016 only counting the main renewable energy resources (hydropower, wind, solar, bioenergy and geothermal).

3 Energy demand profile

3.1 Introduction

The first step that should be revised are the Spanish climatic conditions. Taking into account the zone, Spain is divided into a North Atlantic weather zone [80] with soft, cold, and wet winters; a continental climate zone, which is located inside the peninsular area corresponding to Castile, Madrid, Aragon, Andalusia and Extremadura (characterized by hot summers but very low temperatures in winter and often accompanied by heavy snowfall); and a Mediterranean climate zone, corresponding to the coast.

The Spanish monthly average distribution for the minimal temperatures is given in Table 5. In terms of seasons, winter presents days with an average minimum temperature below or equal to 5ºC, and there are quite several frost days (over 130 – 150 days yearly have a minimum temperature lower or equal to 5ªC), being more severe at the inland zone, in the Atlantic Bank, and in the area of the Pyrenees [20].

Monthly average of minimal temperatures in Spain.

	Minimal average (°C)	Maximum value	Minimum value
January	3.1	9.9	−3.5
February	4.0	10.6	−2.7
March	5.3	11.4	−1.6
April	7.0	12.7	1.0
May	10.2	15.2	4.7
June	13.7	18.3	8.1
July	16.3	21.1	10.3
August	16.6	22.0	10.3
September	14.1	20.2	7.1
October	10.4	16.7	3.4
Novemeber	6.5	13.4	−0.5
Decemeber	4.4	11.0	−2

Table 5. Spanish monthly average distribution

The average requirements for daily sanitary hot water (DHW), heating in 130 – 150 days and electricity for a typical dwelling with four people can be expressed as:

$$e_{av} = n_r \cdot n_{peop} \cdot (dshw) \cdot \Delta T_l \cdot Cp_l \longrightarrow e_{av} = 1.369 \cdot n_r\ (kW)\ ;\ e_{elec} = 0.409 \cdot n_r\ (kW)$$

These needs are averaged for a year in domestic sanitary hot water, four to five months for heating and a year of electricity needs. If these total average needs are considered in function of residence types, practically, and equilibrium is found because multi-family residential housing represents 53% of total consumption, whereas single-family housing represents the remaining 47% of consumption.

Then, examining a great deal of dwellings, total energy consumption is practically equilibrated between these two types of dwellings. This equilibrium is a consequence of the higher number of flats with respect to the number of single-family dwellings and the differences in their energy needs.

At the following figure it can be seen the energy consumption distribution in regards the different electrical appliances if compared between single and multi-family housings.

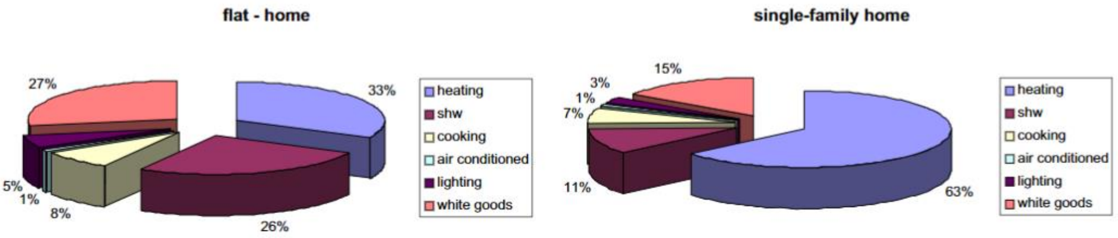


Figure 28. Composition of the energy consumption regarding the residence type in Spain

It is possible to establish the same consideration for electricity consumption. The average percentage breakdown for cooking, refrigeration and lighting (among others) can be seen in Figure 28. The average electricity consumption has a standby fix consumption of 124·n_r (kW) and a variable consumption of 285·nr (kW) with and evolution of the peak demand shown in Figure 30.

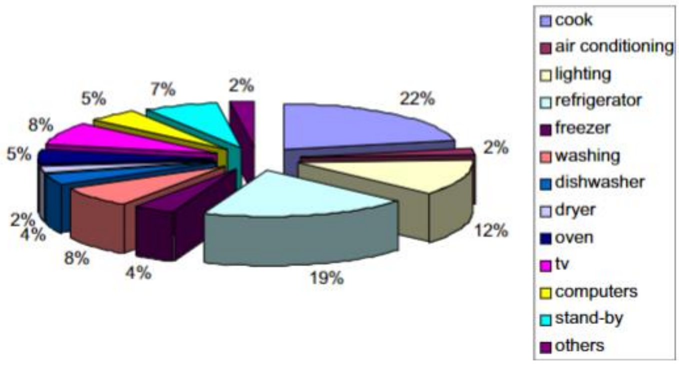


Figure 30. Average percentage distribution for electricity demand in Spain

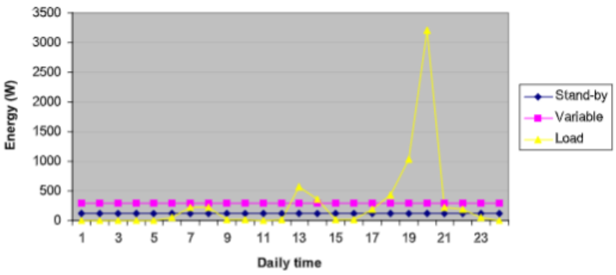


Figure 29. Daily avg. evolution for the residential electricity demand in Spain

The average values of the demand profile in the three main Spanish climatic zones, assuming the same load factors for sanitary hot water, heating and electricity demand, are summarized in Table 6.

Climatic zone	dshw needs (kW)	Heating needs[a] (kW)	Power needs (kW)
National average	$0.227n_r$	$2.356n_r$	$3.330n_r$
North Atlantic	$0.257n_r$	$1.969n_r$	$3.630n_r$
Continental	$0.259n_r$	$3.446n_r$	$3.326n_r$
Mediterranean	$0.199n_r$	$1.739n_r$	$3.263n_r$

[a] In 150 days.

Table 6. Consumption needs in daily sanitary heat water, heating and electricity per dwelling and climatic zone in Spain

A comparison between the North Atlantic zone and the national average shows differences such as softer temperature conditions in winter but higher electricity and DHW needs. Within the Continental climatic territory, there is a higher contrast in temperatures in winter.

For its part, the Mediterranean coast's climate's has the lowest heating requirements due to its warm and soft winter temperatures.

3.2 Unitary calculation

In the previous section it has been shown how it could be calculated the demand profile of the Spanish country with average numbers. In this section is going to be calculated the demand profile for both single-family and multi-family housing and later on these numbers will be extrapolated to all the dwellings at the city of Barcelona.

First, it has been chosen the usual home appliances that all the houses should have nowadays considering the standard of living of the city. At the Table 7 below are shown those appliances as well as its power and energy consumption (standard consumption).

	Power (W)	Power (kW)	Single-family (kWh/d)	Multi-family (kWh/d)
Kitchen (bulbs)	**360**	**0.36**	**1.44**	**1.44**
Living room (bulbs)	480	0.48	1.92	1.92
3 rooms and 1 bathroom (bulbs)	**660**	**0.66**	**1.98**	**1.98**
Ext (bulbs)	180	0.18	0.72	0.72
Fridge	**890**	**0.89**	**13.35**	**21.36**
Satellite TV	156	0.16	0.62	0.62
Computer and Printer	**25**	**0.03**	**0.10**	**0.10**
Washing machine	375	0.38	0.75	0.75
Iron machine	**1500**	**1.50**	**1.50**	**1.50**
Oven	950	0.95	0.95	0.95
Heater	**1500**	**1.50**	**1.50**	**1.50**
Air conditioning	1300	1.30	1.10	1.30
Microwave oven	**1200**	**1.20**	**2.40**	**2.40**
Others	200	0.20	0.80	0.80
TOTAL	**9776**	**9.78**	**29.13**	**37.34**

Table 7. Unitary power and energy consumption for single and multi-family dwellings

Those consumptions may vary depending on the month of use. For example, the heater is going to be turned on the winter season, so that means that the hours of use per day are going to increase, and the same happens with the air conditioning, as meanwhile the heater is not going to be consuming any energy because it is going to be turned off, the air conditioning is going to be consuming (less energy because its power) depending on the hours of use per day.

But those numbers are useful in order to provide an example picture of which are the separate consumption and to make a general idea of which are the needs of the different types of houses in terms of energy demand.

So, what it has been made is taking these numbers and multiply them for the numbers of days a month and thus, be able to provide the consumption per month in a yearly basis, as the following chart is showing.

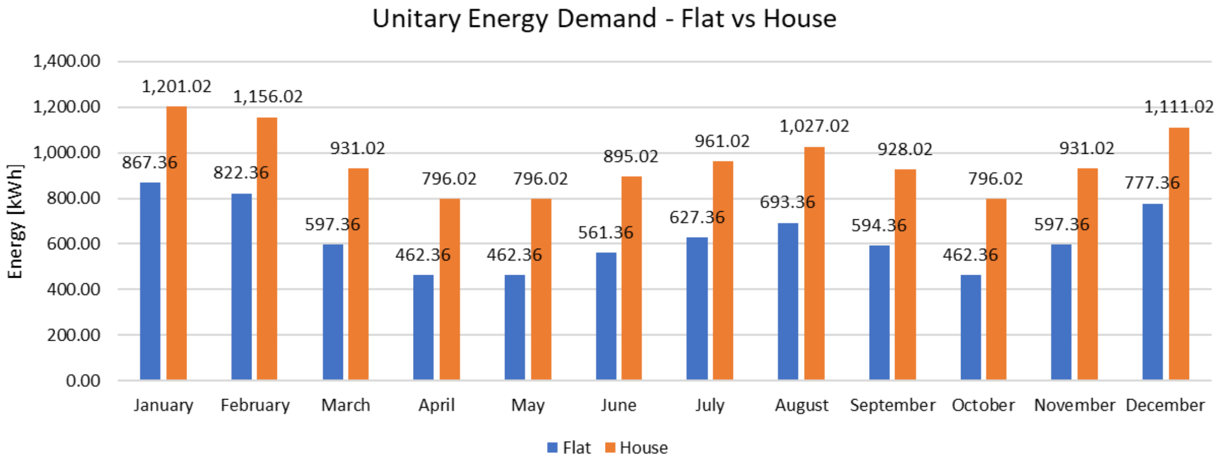


Chart 5. Demand profile flat vs. house

As it can be appreciated at the Chart 5 above, the monthly consumption for a single-family house (household) it is roughly the double compared with a multi-family house, due to its larger extension, more home appliances and more area to cover with energy, among other factors.

Besides, it is interesting to have a look to the unitary consumptions, in Charts 6 and 7, in order to be able to see which are the appliances that are impacting the most in the overall consumption of the building, and be able to reduce this consumption trying to reduce the use of those appliance whose are consuming more or try to buy those whose efficiency is the best.

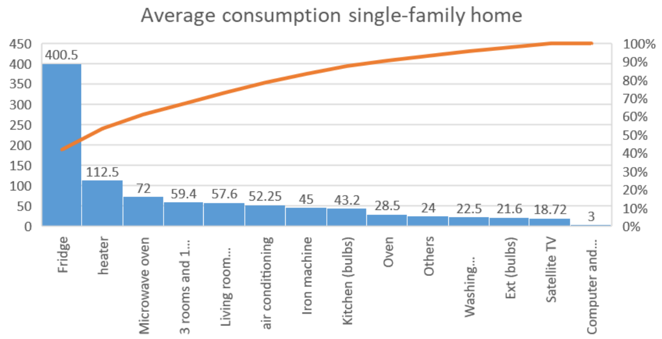


Chart 7. Home appliances consumption (single-family house)

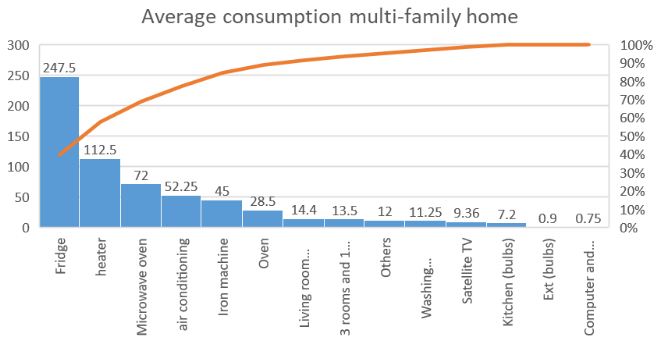


Chart 6. Home appliances consumption (multi-family house)

On both cases, and as it was expected, the appliance that is consuming the most if the fridge because it is barely running the entire day. The heater, the air conditioning and the microwaves are the ones following the fridge in terms of consumption. This is the reason why they should have a rational use and an optimal efficiency in terms of cost and consumption decrease.

3.3 Barcelona demand profile

After calculating the unitary demand for a model house, the next step to proceed on is to extrapolate this calculation to the whole population and dwellings for the city of Barcelona, in order to be able to know which is the whole demand of the city and, afterwards, be able to provide a solution system to supply energy to the houses.

First, it is needed to allocate the city and explain how it is divided. Barcelona is situated inside one of the multiple regions which the Spanish country is divided, which name is Catalunya. At the same time, inside Catalunya there are four provinces which are Lleida, Tarragona, Girona and Barcelona.

Inside the province of Barcelona there is a last subdivision for the Barcelonès province, as it can be seen in the Figure 31: the regions are Badalona, Barcelona city, Hospitalet de Llobregat, Sant Adrià del Besòs and Santa Coloma de Gramanet.

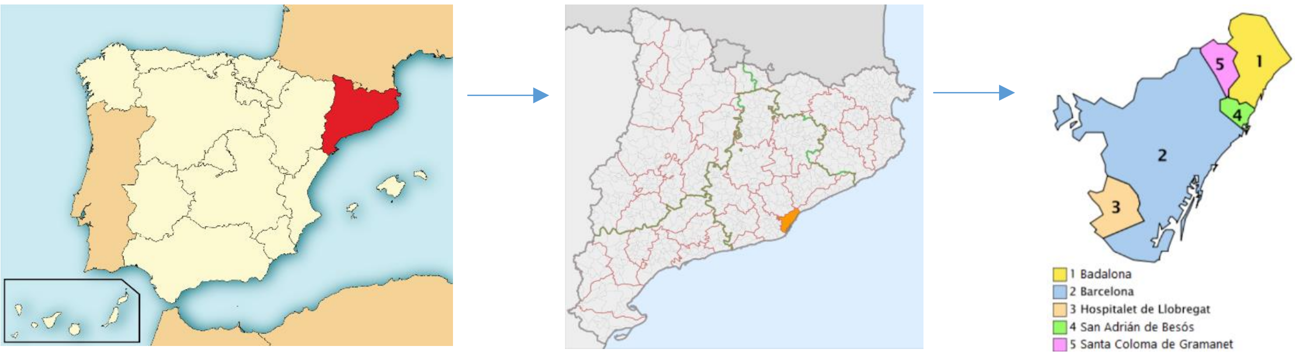


Figure 31. Localization and description of the subdivisions of Barcelonès province

The study of the demand profile is based on the whole province, including the five last subdivisions (but the most populated one is Barcelona city).

At the Figure 32, on the left, it can be seen the number of different types of houses. The last data available is from 2007 that, despite is an old statistic, it can give an idea of how many houses does Barcelona have. So as the Table 8 shows, Barcelona is composed by 32,400 single-family houses and 858,400 multifamily houses.

Habitatges segons tipus d'edifici. Barcelonès.

	2007
Unifamiliar	32,4
Unifamiliar adossat	..
Plurifamiliar	858,4
Total	**896,9**

Figure 32. Number of dwellings by type.

	Year 2007
Single-Family House	32,400
Multi-Family House	858,400
Total	**890,800**

Table 8. Number of dwellings by type. Study version

So, basically, the procedure followed in order to calculate the amount of energy that needs to be supplied to the city, it has been a basic multiplication for each category of house by the unitary amount of energy that the model houses mentioned before need.

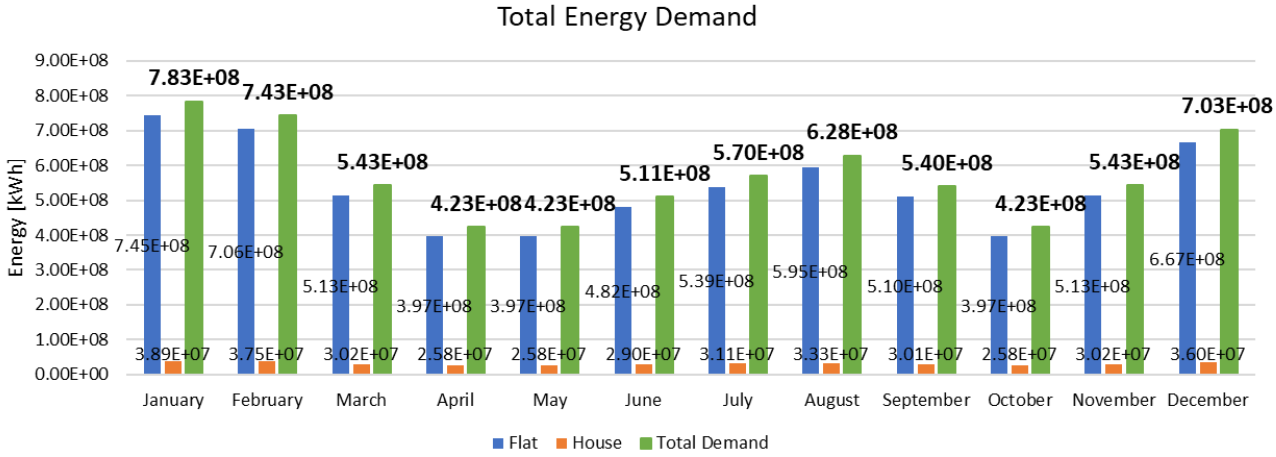


Chart 8. Total energy demand of Barcelona

In the Chart 8 above, it can be appreciated what it has been mentioned before, that even though the consumption is almost the double in a single-family house than in a multi-family one, the number of multi-family houses is much higher than the single-family ones, so that explains the huge difference between the consumptions of the two different categories.

So basically, in order to have a perspective of the consumptions that have been analysed before, in the Table 9 there is a summary of all this data.

	Single-Family House	Multi-Family House	Total
Consumption average (kWh/mth)	960.77	627.11	1,587.88
Unitari consumption (kWh/yr)	11,529.24	7,525.32	19,054.56
Nº Houses	32,400	858,400	890,800
Monthly average (GWh/mth)	31,128.95	538,311.22	569,440.17
Yearly total (MWh/yr)	373.55	6,459.73	6,833.28

Table 9. Summary table for single and multi-family house

Once all these calculations are done, it could be said that the demand profile for the city of Barcelona has been developed and the next steps is move on to the simulation procedures, trying to cover this demand as much as possible, without forgetting the economic side which is going to be one of the important parameters to consider.

4 System Advisory Model simulation analysis

4.1 Solar PV system

4.1.1 Introductory examples

Before starting with the procedures of simulation analysis with SAM it is needed to perform some basic calculations. Those calculations are based on know how many panels will be needed in the implementation of the photovoltaic system. They are done as it follows:

$$\overbrace{\frac{285\,W}{1000}}^{\text{Nominal Power}} \cdot \overbrace{8h}^{\text{Sun hours available}} = \overbrace{2.28\frac{kWh}{day}}^{\text{Energy production per panel}}$$

$$\frac{\overbrace{1201.02\frac{kWh}{month}}^{\text{Maximum energy demand}}}{30\ \frac{days}{month}} = 40.034\frac{kWh}{day}$$

$$\frac{40.034\ \frac{kWh}{day}}{2.28\ \frac{kWh}{day}} = 17.56\ \cong \overbrace{18\,panels}^{\text{Number of panels needed}}$$

$$18\,panels \cdot 1{,}68\frac{m^2}{panel} = 30.24\,m^2$$

In order to proceed with those calculations, it has been chosen a solar panel module, specifically the *SolarWorld Industries GmbH Sunmodule Protect SW 285 mono* with a nominal power of 285 W per unit alongside with the inverter model *SMA America SB3800TL-US-22 [240V]* with a nominal voltage of 240 V. Assuming eight hours of sun per day, mostly in the summer season, in the region of Barcelona, the energy that every panel could produce is 2.28 kWh/day.

Considering the pic of energy demand among all the months of the year, the highest value (single-family house) is 1,201.01 kWh/month and dividing by 30 days that every month has, it is possible to know the amount of energy that the house demands per day, which is 40 kWh/day approximately.

Then, divining the daily energy demand by the energy that every panel can produce, it is possible to know the quantity of panels and the area needed to build the system in order to supply the energy requested, in this case, **18 panels** and **30.24 m^2** are needed.

It is needed to comment that those are theoretical numbers, and, for instance, the counting of losses is not considered in those calculations so, these numbers may vary when including these inputs in the simulation system, as it is going to be shown after.

Besides, this is an optimistic example due to that is not possible to have eight hours of sun per day during the whole year, as this only happens in the summer season but not in the winter one for example. Due to that, later is going to be shown another example in which this parameter is going to change and so that it can be adapted more to the real cases.

Going forward, showing up next the results of the simulation done with the software *SAM Energy (System Advisor Model)* for the single-family house example, with 18 panels installation and a total installed capacity of 5.18 DC kW.

Metric	Value
Annual energy (year 1)	8,131 kWh
Capacity factor (year 1)	17.9%
Energy yield (year 1)	1,569 kWh/kW
Performance ratio (year 1)	0.81
Levelized COE (nominal)	8.54 ¢/kWh
Levelized COE (real)	6.81 ¢/kWh
Electricity bill without system (year 1)	$1,482
Electricity bill with system (year 1)	$645
Net savings with system (year 1)	$838
Net present value	$3,322
Simple payback period	12.5 years
Discounted payback period	NaN
Net capital cost	$13,973
Equity	$0
Debt	$13,973

Table 10. Energy summary 18 panels

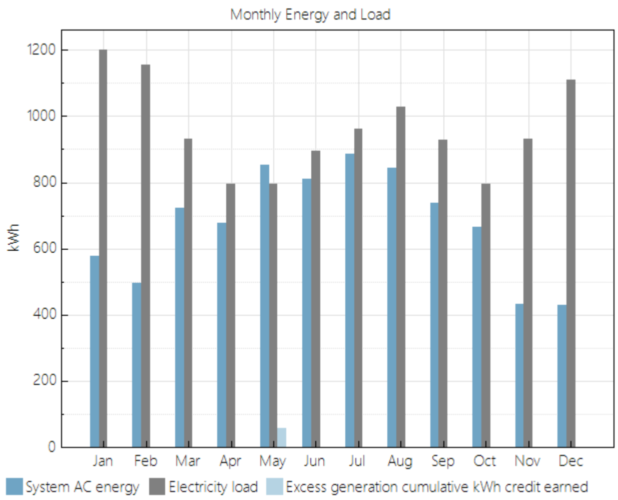


Chart 9. Demand coverage 18 panels

On the Table 10, on the left side, it is possible to see the results for the first year where the system is producing 8,131 kWh/year with a capacity factor of 17.9% and an NPV of $3,322 which means that the investment done is worth it and the installation costs would be defrayed with the savings that this system is going to provide.

However, on the Chart 9, on the right side, it is shown the energy demand (grey bars) compared with the energy supply (blue bars) by this system. It is possible to see that the demand is not totally covered in almost all the months during the year (only in May it is possible to achieve the level of demand needed and create excess of energy generated which the software is counting on the following month). The demand coverage in this case is roughly the 73%, with 18 panels and 6kW DC of desired array size (check Annex for the full report) as planned before.

Besides, as mentioned before it is important to check the economic side. On the Figure 33 below, it is possible to see the payback (time needed for the investment to be recovered).

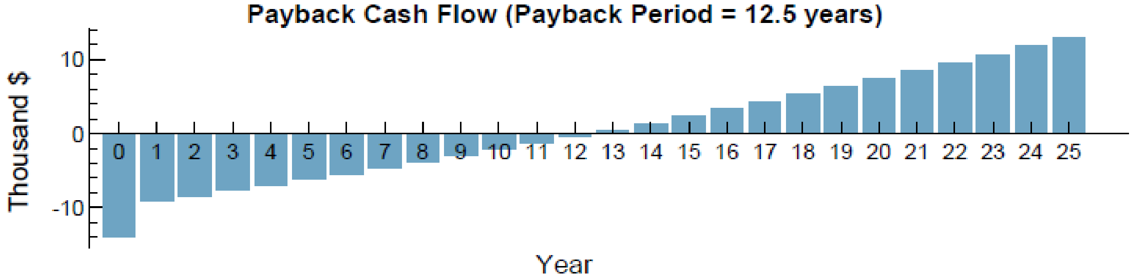


Figure 33. Payback cash flow 18 panels

As it can be seen, there are needed 12.5 years in order to start earning benefits from the system but could be a feasible option for some users that might want to implement this solar system model.

Instead of building 18 panels, it has been carried out another test with 9 more panels being a total of 24 and an installed capacity of 6.91kW DC. The results are the following:

Metric	Value
Annual energy (year 1)	11,010 kWh
Capacity factor (year 1)	18.2%
Energy yield (year 1)	1,593 kWh/kW
Performance ratio (year 1)	0.83
Levelized COE (nominal)	8.47 ¢/kWh
Levelized COE (real)	6.76 ¢/kWh
Electricity bill without system (year 1)	$1,482
Electricity bill with system (year 1)	$542
Net savings with system (year 1)	$940
Net present value	$2,306
Simple payback period	15.1 years
Discounted payback period	NaN
Net capital cost	$18,631
Equity	$0
Debt	$18,631

Table 11. Energy summary 24 panels

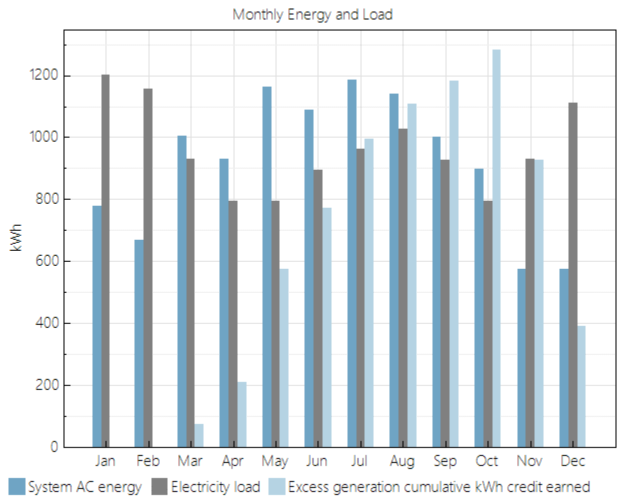


Chart 10. Demand coverage 24 panels

In this case, the payback period has increased to 15.1 years but the NPV is still positive, as the Table 11 shows, which means that the investment on the panels and the installation is going to be worth, and the annual production of energy is a 35% more than the previous case with a demand coverage of a 94% as it can be seen at the Chart 10, leaving partially covered the months of January and February. The following months are covered whereas with self-production or with the excess of energy generated that it is been supplied when the production is not enough to cover the demand.

But, as mentioned before, these results are calculated in an optimistic scenario where the hours of sun are the ones corresponding to the summer seasons. Below, are shown the calculations where the hours of sun decrease (winter season):

$$\overbrace{\frac{285\,W}{1000}}^{\text{Nominal Power}} \cdot \overbrace{5.3h}^{\text{Sun hours available}} = \overbrace{1.51\,\frac{kWh}{day}}^{\text{Energy production per panel}} \longrightarrow \frac{\overbrace{1201.02\,\frac{kWh}{month}}^{\text{Maximum energy demand}}}{30\,\frac{days}{month}} = 40.034\,\frac{kWh}{day}$$

$$\frac{40.034\,\frac{kWh}{day}}{1.51\,\frac{kWh}{day}} = 26.5 \cong \overbrace{27\,panels}^{\text{Number of panels needed}} \longrightarrow 18\,panels \cdot 1{,}68\,\frac{m^2}{panel} = 45.36\,m^2$$

Now, if the hours of sun available per day decrease until 5.3 as an average, redoing the calculations it is obtained that the numbers of panels needed in order to cover the highest peak of demand is 27.

Including these changes in the simulation software the results obtained are as follows:

Metric	Value
Annual energy (year 1)	12,403 kWh
Capacity factor (year 1)	18.2%
Energy yield (year 1)	1,595 kWh/kW
Performance ratio (year 1)	0.83
Levelized COE (nominal)	8.46 ¢/kWh
Levelized COE (real)	6.75 ¢/kWh
Electricity bill without system (year 1)	$1,482
Electricity bill with system (year 1)	$490
Net savings with system (year 1)	$992
Net present value	$1,809
Simple payback period	16.2 years
Discounted payback period	NaN
Net capital cost	$20,959
Equity	$0
Debt	$20,959

Table 12. Energy summary 28 panels

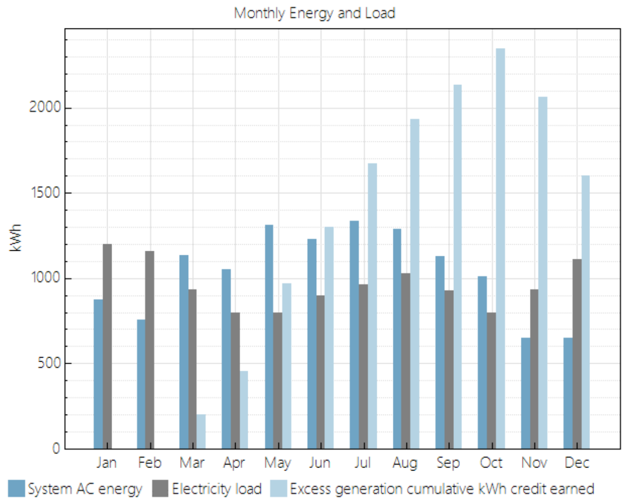


Chart 11. Demand coverage 28 panels

As it was expected, the more panels installed, the more energy can be produced with a total annual energy produced of 12,403 kWh (Table 12). With this setup, the demand coverage can be up to 95% leaving uncovered only the 30% of the demand for the first two months (January and February), as shown on Chart 11.

It can be appreciated as well, that in this case the excess of energy generated is huge. However, could be a feasible option to consider because, depending on the country, there are several policies that let to take profit from this excess of energy produced.

Recently, the Spanish government has approved a law, which allows under certain conditions to the users of renewable systems, to inject the energy that is not used back to the grid alongside with economical compensations [21].

Also, countries like Denmark, have several policies in order to award self-producers and consumers who have an excess of energy generated. The Danish government gives economical compensation (*Premium tariff, Law on the Promotion of Renewable Energy*) which the conditions can be checked in European Commission website [22].

Moving forward, on the Figure 34 below, it can be seen the hourly energy supply distribution during 24h on May 14th, as an example. As this system has no battery implemented, the solar system can only provide energy when it can get energy from the sun, so that, as shown on the picture, the orange area shows the energy that is coming directly from the solar PV system.

As it was expected, around the spring-summer seasons the system is capable to provide energy during 7 or 8 hours continuously, so from 8 am in the morning until 4 or 5 pm in the afternoon it is possible to provide energy coming from this renewable source. The blue area is showing the part of energy that cannot be provided from the solar system and it is needed to be supplied directly from the grid.

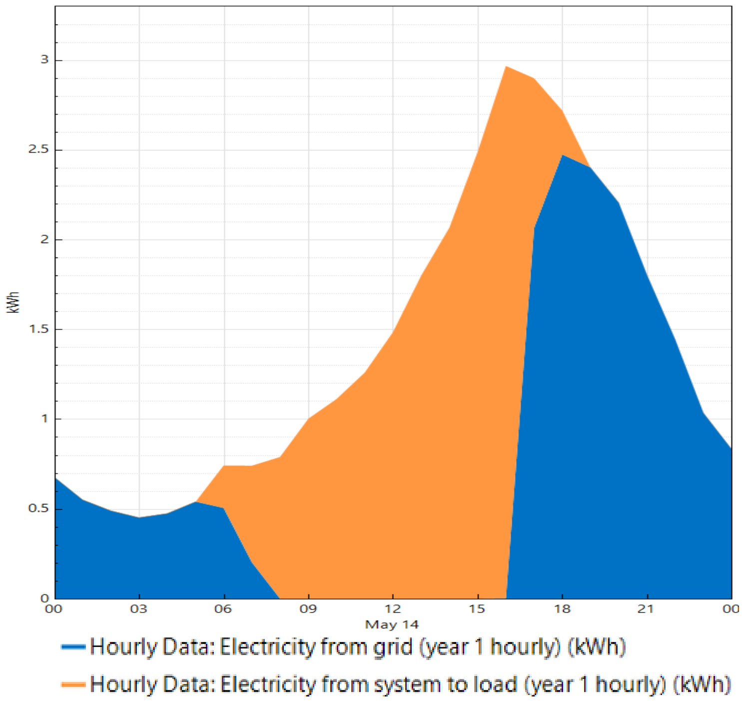


Figure 34. Hourly power distribution 28 panels

Later on, in this work, is going to be shown how this graph can change with the implementation of a battery and, as well, how this extra cost that the battery involves is impacting in the economic side and it will be considered or not at the time of building this kind of system in a real case.

4.1.2 Parameters optimization

The examples shown on the previous section have been generated with previous optimization procedures in order to extract the maximum energy from each system.

One of the parameters that impacts on the amount of energy produced by a PV system is the panel's orientation which is subdivided in two angles: Azimuth which rotates around Y axis and Tilt which is rotating around X or Z axis, as shown on the Figure 35 below.

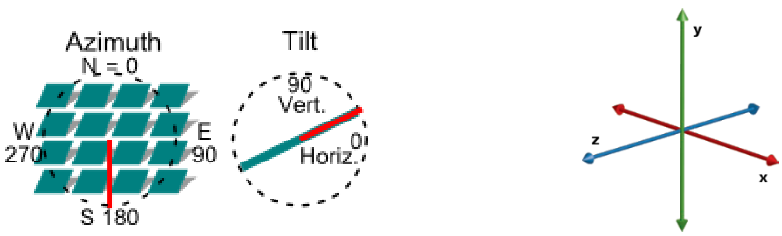


Figure 35. Azimuth and Tilt angles explanation

The software *SAM Energy* has a useful and powerful tool that lets the user optimize the results that are being looking for depending on some requested parameters. As shown on the Figure 36 below, this tool is called *Parametrics* where leads to a dashboard where it can be selected the inputs and outputs which is going to be calculated an iterative process.

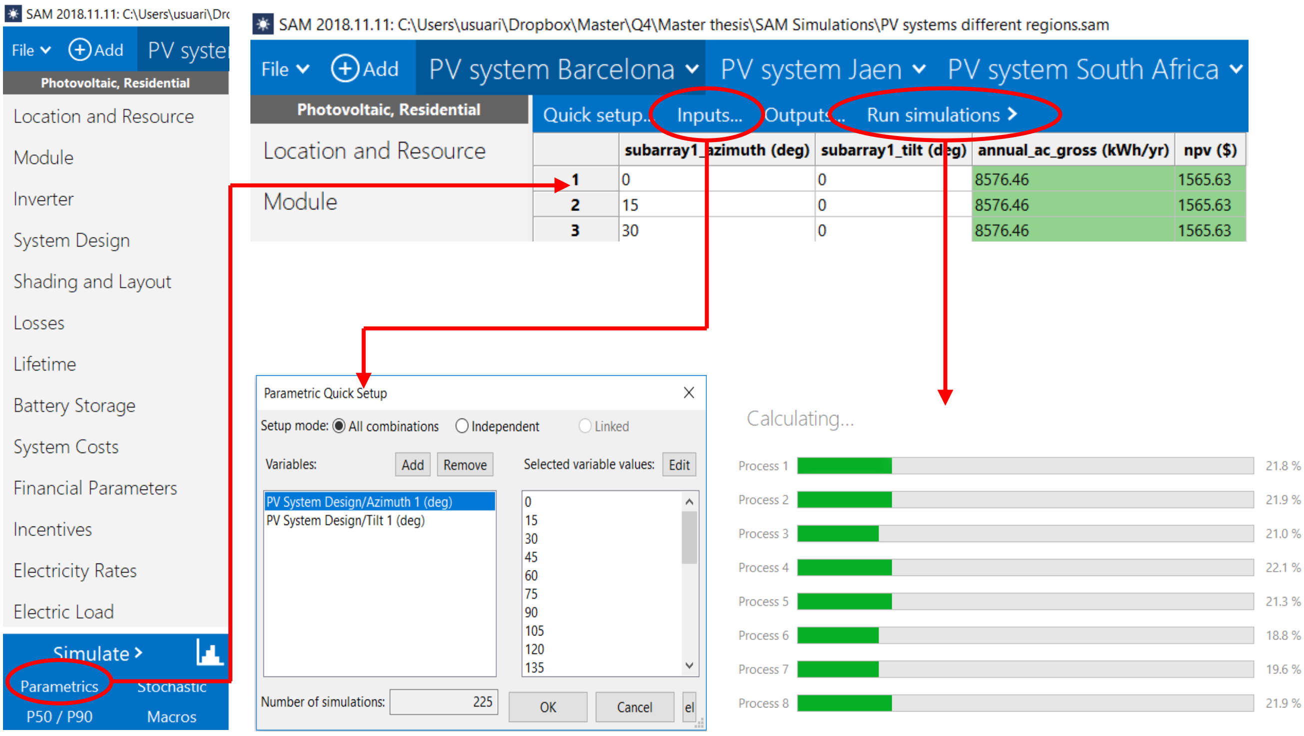


Figure 36. Optimization steps for energy parameters

After all the iterations are calculated, the program shows every output selected according to each value of each input determined and returns the information summed up on the Chart 12 below:

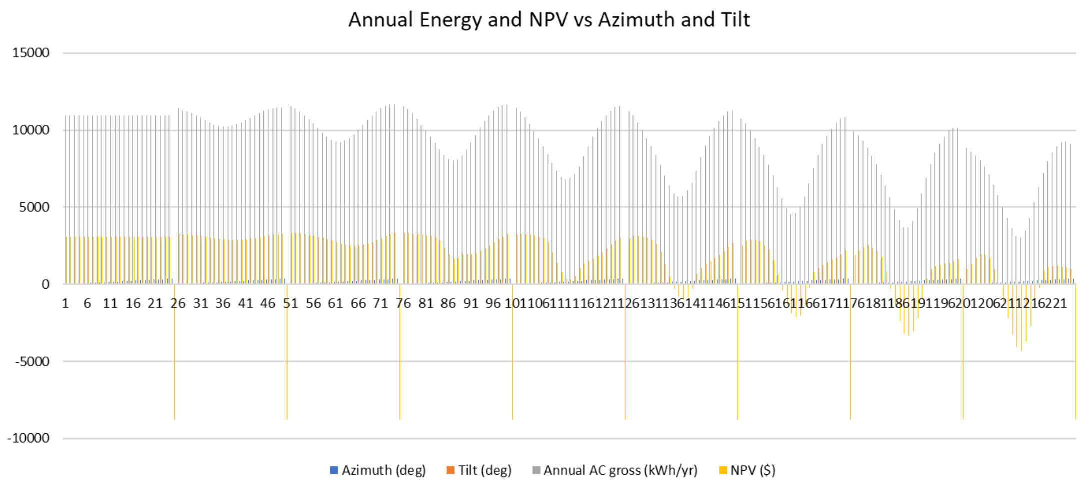


Chart 12. Energy optimization results

So, basically, the information that it is intended to extract from this chart, is the maximum energy produced per year, *Annual AC gross (kWh/yr)*, and the positive and highest value of net present value, *NPV*, so that, the most important outputs are measured, on the engineering side, the amount of energy generated, and on the economical side, the parameter that measures the viability and profitability of the investment done.

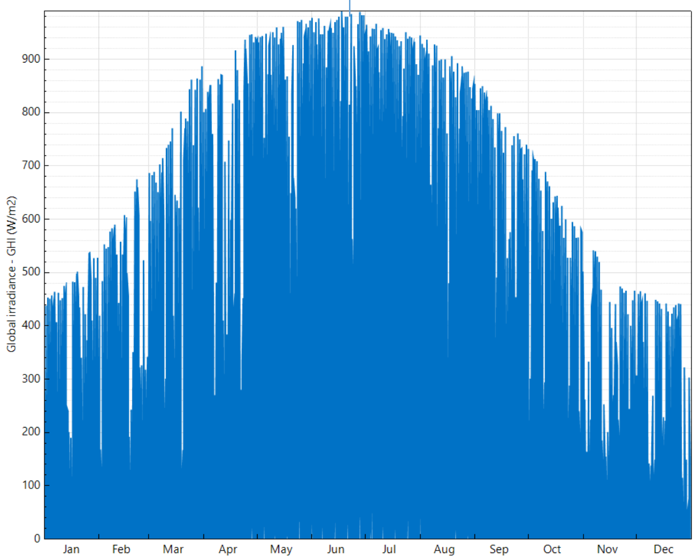
4.1.3 Battery cases

In this section is going to be analysed the use of batteries in the solar system, which are the positive and negative points of implementing them.

At first can be idyllic the idea of installing a battery so that the solar system can be completely autonomous, because the batteries can be charged during the day light, at the same time that the system is providing energy to the load and then use this energy stored in night hours in order not to run out of energy.

But so far, the batteries nowadays are expensive, and they need to be constantly changed every specific period because they have a limited life and this is increasing the price and thus, this needs to be considered at the investment. Besides, the efficiency of them it is not what it was expected at first, because the results are not as good as it was thought at the beginning.

First, it is needed to show the solar irradiance, on the Figure 37 below, of Barcelona area. As it can be seen, the irradiance keeps increasing from 450 W/m^2 until the maximum point around June – July months, achieving the highest value of 979 W/m^2 of Global Horizontal Irradiance, and after it comes back to the decreasing trend the rest of the year.



$$GHI = 979\ \frac{W}{m^2}$$

$$DNI = 897\ \frac{W}{m^2}$$

$$DHI = 128\ \frac{W}{m^2}$$

Figure 37. Barcelona's irradiation yearly distribution

The Global horizontal Irradiance (DHI) is the total irradiance from the sun on a horizontal surface on Earth. It is the sum of Diffuse Horizontal Irradiance (DHI, is the radiation at the Earth's surface from light scattered by the atmosphere) and the Direct Normal Irradiance

(DNI) after accounting for the solar zenith angle of the sun z [23], as shown in the following formula as follows:

$$GHI = DHI + DNI \cdot \cos(z)$$

On the Charts 13 (solar PV system with battery included) and 14 (only batteries energy supply) it can be seen the yearly evolution of the behaviour of batteries under the solar irradiance shown before. As it can be appreciated, there are three different types of batteries (blue, orange and grey lines) with different configurations and sizes, all together compared with the total energy demand for a single-family household (yellow bars).

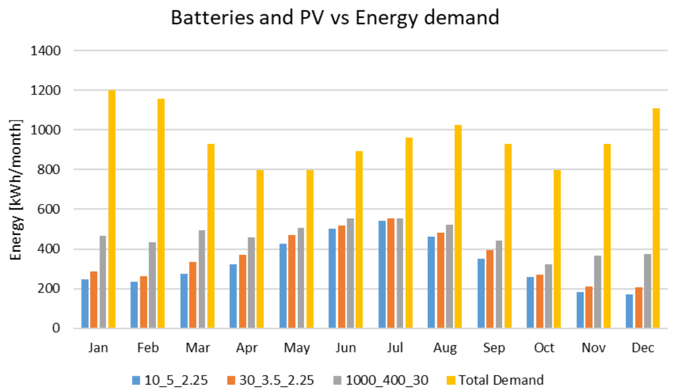


Chart 14. Solar PV systems with batteries included

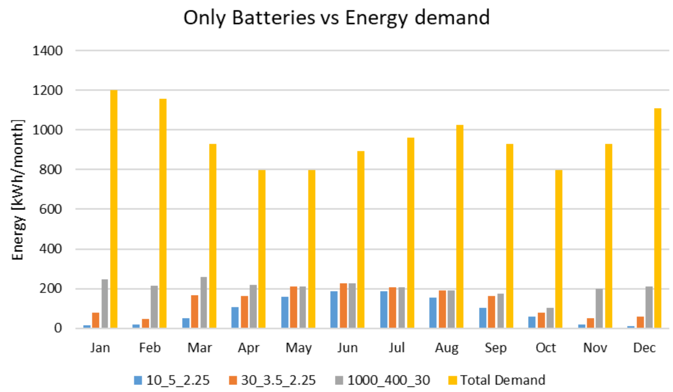


Chart 13. Only batteries performance

The smallest battery, the blue one, can supply a very reduced portion of energy, especially in the first and last months, where the irradiance is reducing until 450 W/m^2. But when the irradiance increases, the PV system can provide energy at the same time as it can store energy at the batteries, and those, can supply this energy to the load.

On the other hand, it has been done the same test but with an extremely larger battery (grey line) in order to see if the result could vary in a huge proportion. But the only usable outcome turned into a better performance on the months where the irradiance is lower.

On the Chart 15, on the right, it is interesting to notice that the behaviour becomes similar at the months where the irradiance is the highest (July) independently of the battery used. These last results lead to think that the energy supply is similar but not the price which is necessary to pay in order to maintain the installation costs, as shown on the Chart 15 below.

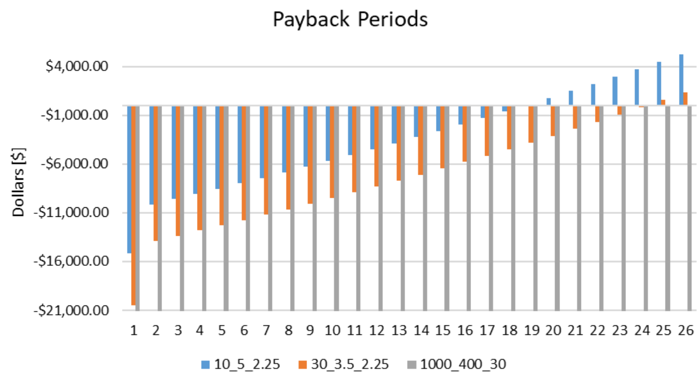


Chart 15. Batteries paybacks period's comparison

As it can be seen, the payback period for the largest battery (grey one), which is the one that provides a better result, it is more than 25 years, what means that the investment is not feasible and worth, because this batter may be oversized and would not be a good option.

On the other hand, the blue battery has a payback period of 18 years and the orange one of 24 years. Even though those paybacks are more reduced than the one shown in the case of the grey battery, a payback greater than 10 years is a point to consider when it comes to make a particular installation of a solar system, plus the price of buying the battery, etc.

So, as predicted before, the results of the batteries are not as good as it was expected before. Even though, in order to provide a reasonable sizing of a battery that could be implemented in a solar installation, it has been carried the following calculations.

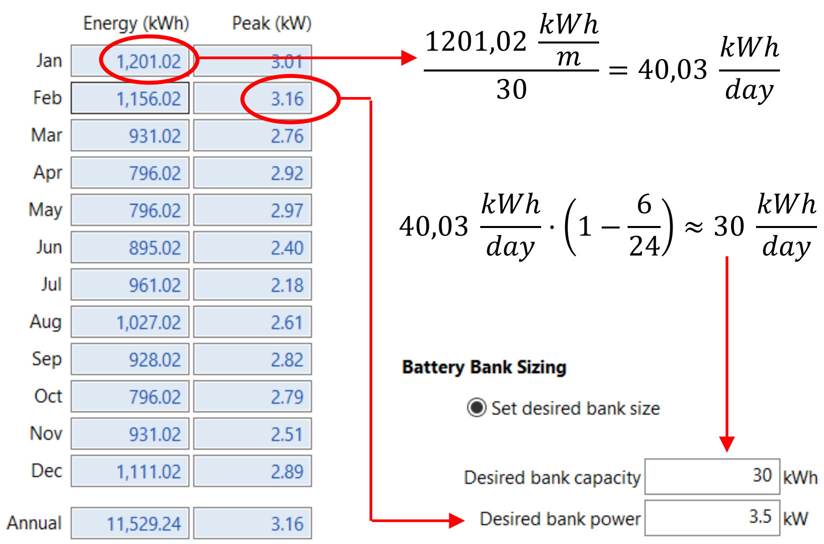


Figure 38. Energy and power peaks single-family house

On the Figure 38 above, it can be seen a yearly distribution for the energy demand for the single-family household. Before proceeding with the calculations, it is needed to explain the concepts of *bank capacity* and *bank power*. The bank capacity it can be explained as the total amount of electricity that a solar battery can store, measured in kWh. On the other hand, the bank power is how much electricity a battery can provide at a given moment (peak), measured in kW.

So, as the table is showing, the highest value of energy that needs to be provided is 1,201.02 kWh per month, that if it is calculated per day, turns out to be 30 kWh/day, so that, the correct bank capacity is 30 kWh. For the bank power, the battery needs to support the maximum peak in the demand, so the highest peak is 3.16 kW and applying a 10% of security margin the bank power of the battery would be 3.5 kW.

Once the battery size has been calculated according to the demand, it is interesting to see how the battery supplies the energy during the day and which is the dependency of the grid and in which percentage, in terms of energy supply.

As seen in the Figure 39 below, there are disposed the different performances of the energy supply for the same day in the middle of the month of May. So, showing 24 hours of energy supply, it is possible to see differences between the three kinds of batteries.

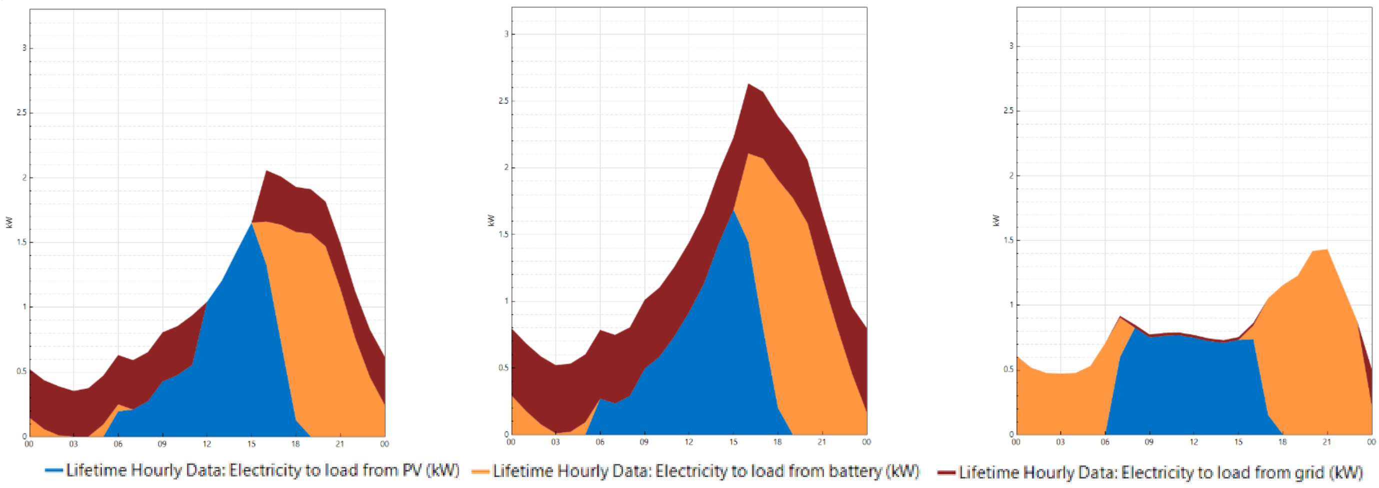


Figure 39. Hourly power distribution comparison between the battery's types

On the left side, it is possible to see how, throughout the day, the energy it is being supplied by the PV system (blue area) and the battery (orange area). But there are some peaks during the day that need to be supplied from the grid, because the system is not able to support this amount of energy.

The same happens on the picture in the centre of the figure, where some peaks are supplied by the renewable system and others need the assistance from the grid. But still, even if the grid is needed sometimes, it is possible to reduce the percentage of energy that needs to be supplied from the grid, so that would turn into a decrease on the electricity bill.

On the right side, it can be seen how the energy distribution and supply during the 24 hours is. As it can be appreciated, there is almost no red area, which is the one pointing to the electricity given from the grid to the load (point of consumption), which would mean that it has been reached almost the 100% of renewable energy production and supply. During the day light hours, the PV system is the one in charge of supplying energy, and during the night hours the battery is giving the energy that the load needs and that cannot be given by the panels.

This last scenario would be the ideal one, where the house can be totally disconnected from the grid as the own system is able to provide all the energy that the demand profile shows. But as mentioned before, it cannot be done because the costs of installation and maintenance of the whole system are not feasible to reach.

So, the next steps to follow is finding the balance between different renewable energy systems available in the region and the economic cost and try to find the maximum percentage of demand coverage.

4.1.4 Barcelona photovoltaic system

All the previous examples were carried out in order to be able to know how possible was to supply energy from a renewable resource as a solar PV system, which are the costs, and which are the key parameters that need to be controlled in order to obtain the maximum benefit and efficiency.

So, going forward with the analysis, the next step in this work is trying to cover the energy demand for the whole city of Barcelona. As shown before, the demand profile for the city has been calculated before and the monthly distribution of energy is the one shown below at Figure 40.

	Energy (kWh)	Peak (kW)
Jan	783,454,976.0	1,963,015.50
Feb	743,369,024.0	2,032,293.00
Mar	542,939,008.0	1,611,491.75
Apr	422,680,992.0	1,552,494.88
May	422,680,992.0	1,575,672.50
Jun	510,870,016.0	1,369,285.50
Jul	569,662,976.0	1,292,721.88
Aug	628,456,000.0	1,596,177.88
Sep	540,265,984.0	1,644,444.25
Oct	422,680,992.0	1,480,297.00
Nov	542,939,008.0	1,465,879.88
Dec	703,283,008.0	1,830,817.38
Annual	6,833,283,072	2,032,293.00

Figure 40. Energy and power peaks Barcelona

As the table shows, the solar PV system needs to be capable to supply a total amount of energy of 6,833 GWh with the maximum peak of 2.03 GW. After simulating this demand profile in *SAM Energy,* the results are the ones shown below at Table 13 and Chart 16.

Metric	Value
Annual energy (year 1)	6,133,558,272 kWh
Capacity factor (year 1)	18.4%
Energy yield (year 1)	1,614 kWh/kW
Performance ratio (year 1)	0.84
Levelized COE (nominal)	8.36 ¢/kWh
Levelized COE (real)	6.67 ¢/kWh
Electricity bill without system (year 1)	$1,034,775,360
Electricity bill with system (year 1)	$323,173,216
Net savings with system (year 1)	$711,602,176
Net present value	$3,576,921,600
Simple payback period	10.7 years
Discounted payback period	21.3 years
Net capital cost	$10,243,965,952
Equity	$0
Debt	$10,243,965,952

Table 13. Energy summary Barcelona solar PV

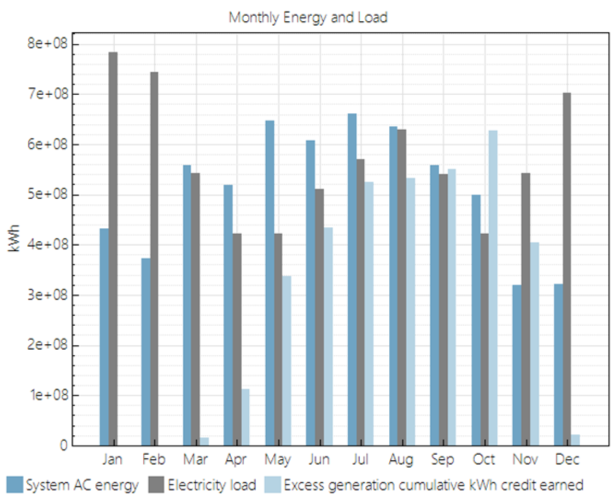


Chart 16. Demand coverage Barcelona solar PV

The solar panels selected are the same as the ones on the previous examples, *SolarWorld Industries GmbH Sunmodule Protect SW 285 mono* model and the inverter is *Advanced Energy Industries AE 1000NX* with 1000 kW AC power. The layout and setup for this case is completely different as the previous examples, as this time there are needed 13,196,280 panels distributed in 329,907 strings in parallel (rows of panels) with 40 panel for each string.

After implementing the optimization procedures explained before for the tilt and azimuth angles, the optimal ones are 40º for tilt and 165º for azimuth, as shown on the Figure 41 below. This picture shows the information related to the modules (panels) and inverters, as well as the total capacity installed which is 3,800 MW of DC power.

Modules	
SolarWorld Industries GmbH Sunmodule Protect SW 285	
Cell material	Mono-c-Si
Module area	1.68 m²
Module capacity	287.96 DC Watts
Quantity	13,196,280
Total capacity	3,800 DC MW
Total area	22,169,749 m²

Inverters	
Advanced Energy Industries: AE 1000NX (3159700-XXXX)	
Unit capacity	1000 AC kW
Input voltage	1100 - 1600 VDC DC V
Quantity	3,455
Total capacity	3,455 AC MW
DC to AC Capacity Ratio	1.10
AC losses (%)	2.00

Array	
Strings	329,907
Modules per string	40
String voltage (DC V)	0.00
Tilt (deg from horizontal)	40.00
Azimuth (deg E of N)	165

Annual Results (in Year 1)	
GHI kWh/m²/day	4.50
POA kWh/m²/day	4.00
Net to inverter	6,338,706,000 DC kWh
Net to grid	6,133,558,000 AC kWh
Capacity factor	18.4
Performance ratio	0.84

Figure 41. Solar PV results

So, coming back to Chart 16, it is possible to see that the demand coverage is quite accurate as all the months are covered (except January and February), either by energy production or energy excess, and the total demand coverage is roughly around the 92%.

Another strong point to comment is the payback period that it is around 11 years (10.7 to be exact) as shown on the Figure 42 below, and the NPV is positive which is showing the viability of the investment that should be carried out by the government of Barcelona.

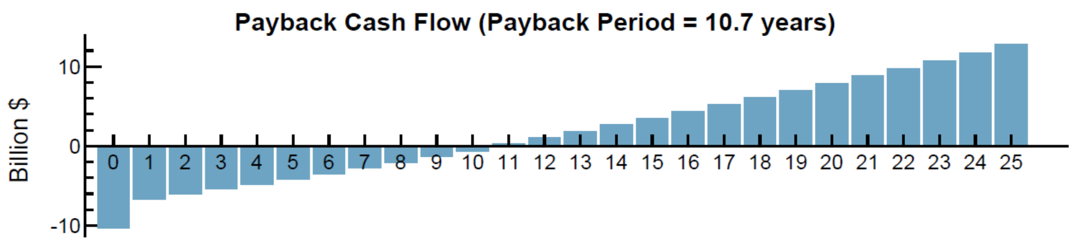


Figure 42. Payback cash flow Barcelona solar PV

As happened on the previous examples and as in this system there is no battery implemented, the solar PV system is producing energy and supplying it to the load during the day light hours. As it can be seen in Figure 43 below, the system is able to provide energy continuously an average time of 8 hours during the summer season (month of May), so that means that it is running from 7 – 8 am until 3 – 4 pm uninterruptedly.

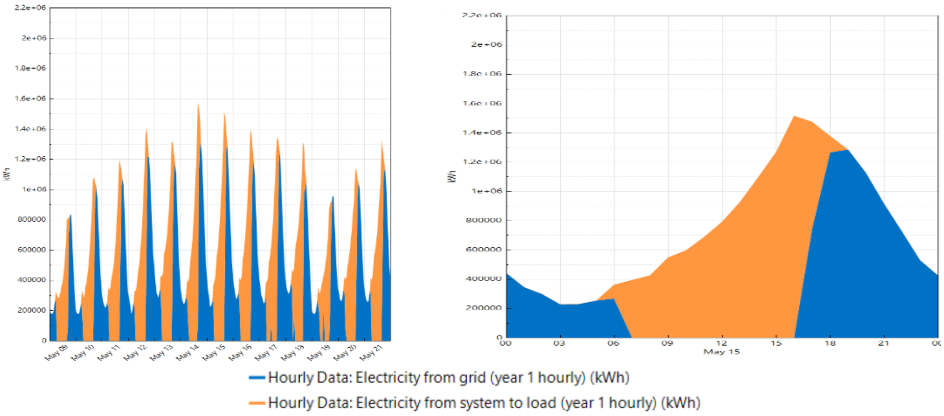


Figure 43. Hourly power distribution Barcelona solar PV system

From 4 pm until 6 pm approximately the system is still working but this time in parallel with the feed coming from the grid, as it is not able to cover all the demand by itself. As it can be seen and as it is obvious, during the night hours it is still needed the grid in order not to run out of energy and thus, some home appliances can keep running such as the fridge, the heater or air conditioning, among others.

In order to carry out this project, as shown before on Figure 41, the area needed in order to build the solar field is around 22.17 km^2 which is such a large extension and it cannot be built in the middle of the city. For that, in this project it is offered two different alternatives shown below in Figure 44.

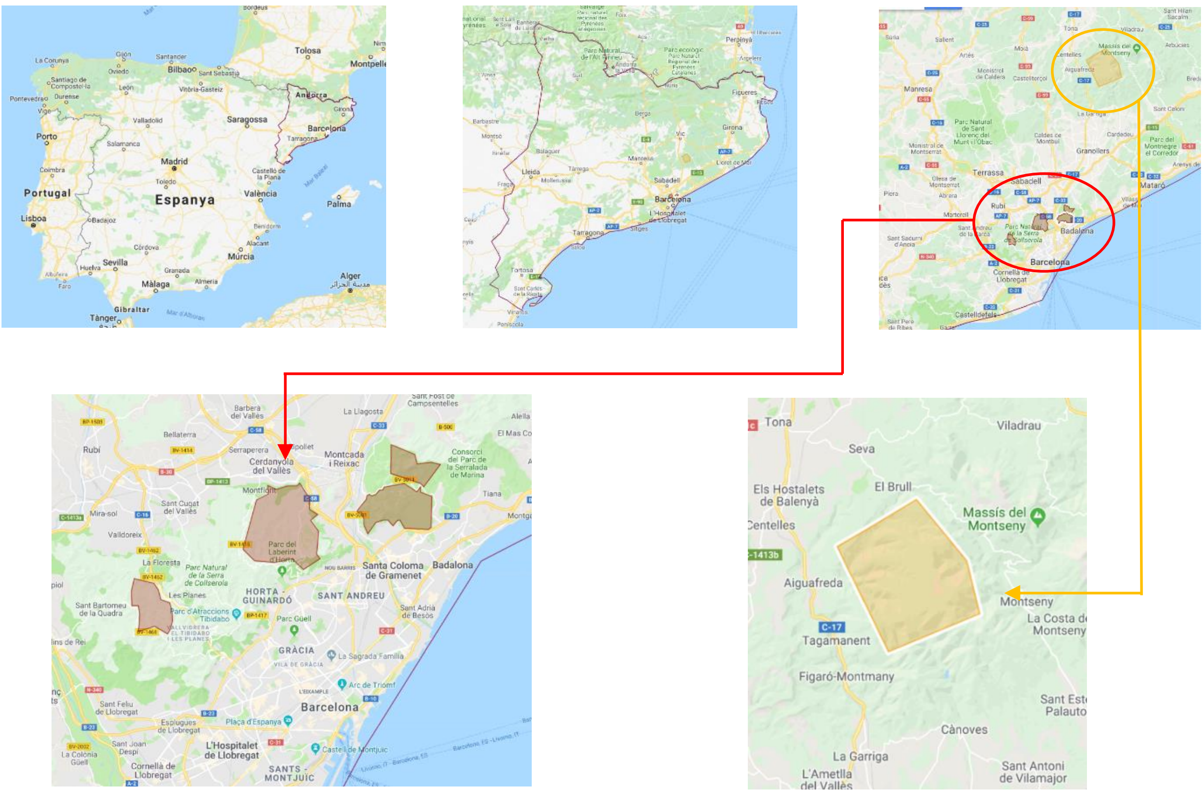


Figure 44. Solar fields Barcelona and Girona

As it can be seen, inside the Spanish territory, there is the Catalonian region. For this project implementation it has been selected two different fields: the first one, on the left, shown in red, is inside the Barcelona metropolitan area and it belongs to the city's government. On the other hand, on the right side, shown in yellow, there a larger area that it is not belonging to Barcelona but to Girona, which is another province and a bit further from the city.

Next, are going to be analysed these two options, altogether with its own pros and cons. As it can be seen on the Figure 45 below, four delimited areas have been selected around the city [24] for the first option of building the solar field. Counting these four areas it comes to a total extension of 23.35 km^2 which is greater than the area needed which has been mentioned before, the 22.17 km^2.

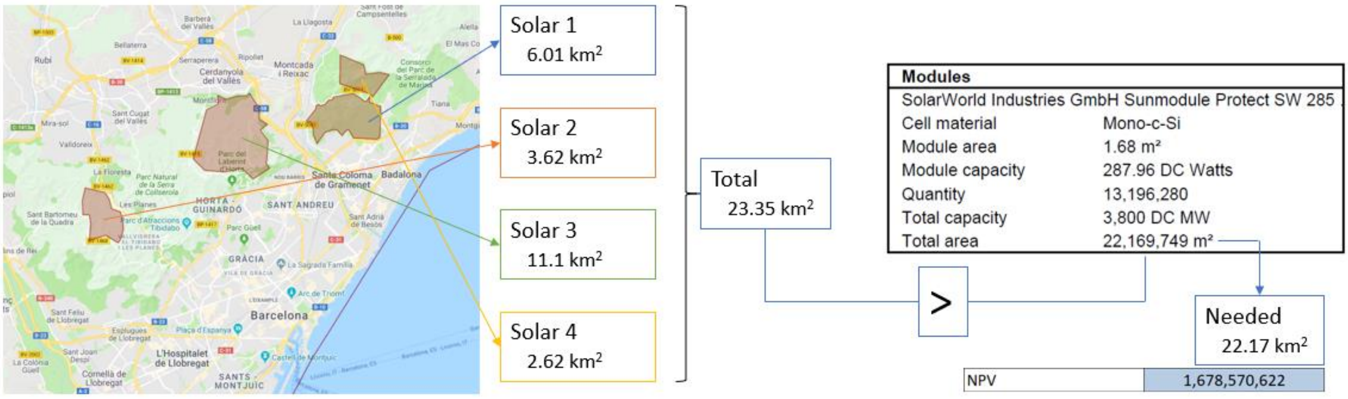


Figure 45. Barcelona solar fields analysis

The value for *NPV* for the area needed according to *SAM Energy* simulations, the 22.17 km^2, is the one seen on the bottom right corner ($1,678M approximately). This amount is only adjusted to the cost of energy and the cost of installation and, besides, to this area needed.

There are several factors that need to be considered when a investment needs to be done in a project like this. For instance, the permissions that are needed to be paid, the labour in order to build the solar field, the materials to build it, the engineers that are needed to be hired for this work and the area where the solar field is going to be place (piece of land).

That is why below, in Figure 46, can be shown the difference between considering the piece of land in the *NPV*. Without the field investment the value rounds $3,576M and considering the price of the land [25] (243.14 $/m^2), it turns into $1,577M).

Without field investment

KEY
Calculated
Input from SAM

RESULTS	
LCOE (real) ¢/kWh	6.67
LCOE (nominal), ¢/kWh	8.36
NPV	3,576,921,542
Payback period, years	10.70
Discounted payback,yrs	21.28

Unidad: euros/m^2

	Año 2018 (trimestre)			
	1°	2°	3°	4°
TOTAL NACIONAL	**163.1**	**162.9**	**155.1**	**157.7**
Cataluña	**185.9**	**175.9**	**174.7**	**174.8**
Barcelona	237.1	215.2	228.3	214.4
Girona	138.1	143.1	140.1	145.9
Lleida	78.6	96.0	72.3	79.4
Tarragona	102.2	116.6	113.1	111.0

With field investment

KEY
Calculated
Input from SAM + BOE

RESULTS	
LCOE (real) ¢/kWh	9.44
LCOE (nominal), ¢/kWh	11.83
NPV	1,577,508,108
Payback period, years	15.70
Discounted payback,yrs	25.00

Figure 46. Economic calculations with and without field investment Barcelona

And so, the payback related to the investment changes, which moves from 10.7 years until 15.7 years, which means 5 more years considering the purchase of the piece of land.

But all these numbers are supposed to happen in the first scenario which was enabling some lands close to the metropolitan area of the city of Barcelona. Moving forward, below is shown on Figure 47 how the situation changes if instead of this scenario, the government of Barcelona decides to buy some piece of land in Girona.

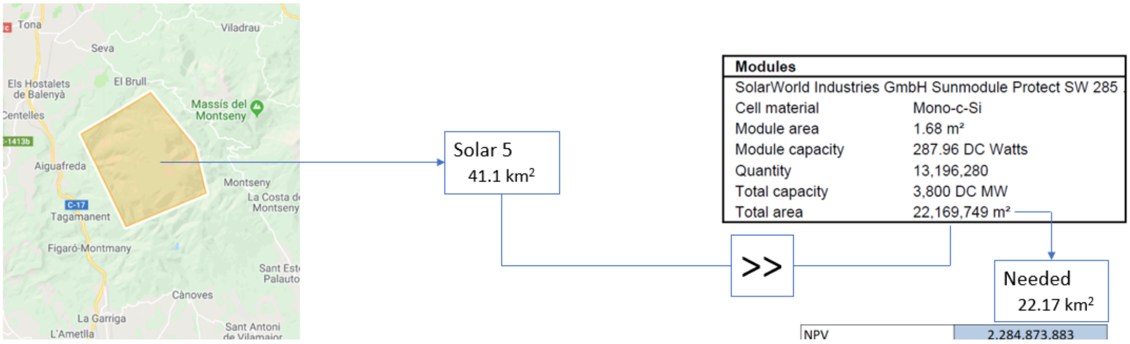


Figure 47. Girona solar field analysis

In this case is feasible to buy only one piece of land but larger than the previous case (almost the double needed for the solar field simulated) and carry out the installation. As it can be seen on the bottom right corner, this time the *NPV* is higher, around $ 2,284M (which means that the investment is even more viable) even if it is calculated with the same area as in the last case (22.17 km^2) because in this scenario the price per m^2 in Girona is cheaper than in Barcelona (165.46 \$/m^2) [25], so that, this allows to buy more land at a lower price.

As it can be seen at the Figure 48 below, marked in green the price for one m^2 is 165.46 \$/m^2 which is cheaper, and it is going to make decrease the effort on the investment. So, as shown at the table with the title *With field investment* it is possible to see that the *NPV* is around $1,181M which number is very similar (a bit lower) than the previous case but considering that the area bought is almost the double. So that will mean that buying the same area the cost will be reduced and the investment would be more worth it.

Without field investment

KEY
Calculated
Input from SAM

RESULTS	
LCOE (real) ¢/kWh	6.67
LCOE (nominal), ¢/kWh	8.36
NPV	3,576,921,542
Payback period, years	10.70
Discounted payback,yrs	21.28

Unidad: euros/m^2

	Año 2018 (trimestre)			
	1º	2º	3º	4º
TOTAL NACIONAL	163.1	162.9	155.1	157.7
Cataluña	185.9	175.9	174.7	174.8
Barcelona	237.1	215.2	228.3	214.4
Girona	138.1	143.1	140.1	145.9
Lleida	78.6	96.0	72.3	79.4
Tarragona	102.2	116.6	113.1	111.0

With field investment

KEY
Calculated
Input from SAM + BOE

RESULTS	
LCOE (real) ¢/kWh	9.99
LCOE (nominal), ¢/kWh	12.51
NPV	1,181,623,391
Payback period, years	16.67
Discounted payback,yrs	25.00

Figure 48. Economic calculations with and without field investment Girona

But this scenario has one disadvantage and it is that the government of Barcelona would need to ask the government of Girona if they can buy this piece of land or which would be the permissions needed in order to be able to access to it, as it is not inside the Barcelona province, thus, they would need to request for it or try to make some profitable deal with Girona in order to be worth it for both sides.

4.2 Wind farm

4.2.1 Onshore turbines

4.2.1.1 Design parameters and introductory examples

Before deep diving in the examples of simulation related with the wind farm cases it is needed to explain what are the parameters that affect to the amount of energy generated and which are the reasons why this occurs.

As shown on the Figure 50 below, one of the parameters that makes the wind turbines power curve change is the rotor diameter. As it can be seen on the figures on the right side, (Figure 50), the bigger is the rotor diameter the faster grows the power curve.

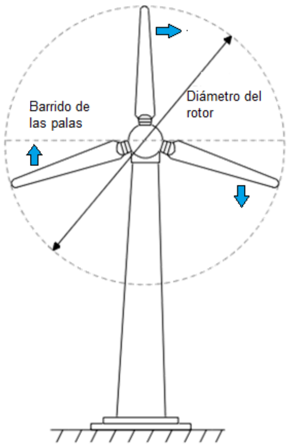


Figure 50. Rotor diameter

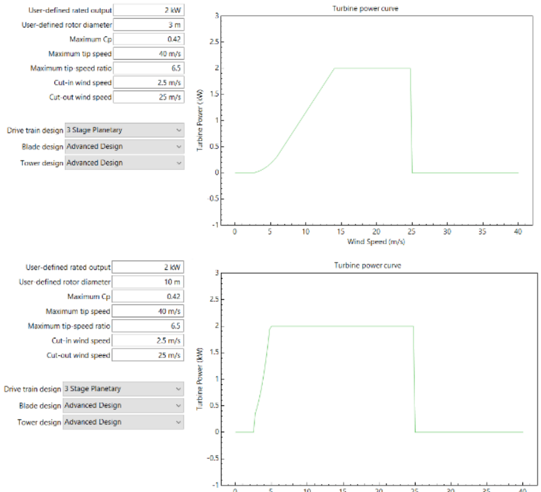


Figure 49. Rotor diameters 3m and 10m

This fact is helpful when, for example, the wind speed is not that high, so that the wind turbine can start generating energy earlier in the curve and so that, there is no need for high wind speeds, which is exactly the case that is happening in the Spanish country, which wind speed is around 3 – 4 m/s as mentioned on previous sections.

So, this is the reason why it has been simulated a wind turbine of 2 kW of power with 17m of rotor diameter. Below, on the Figure 51, can be appreciated the power curve.

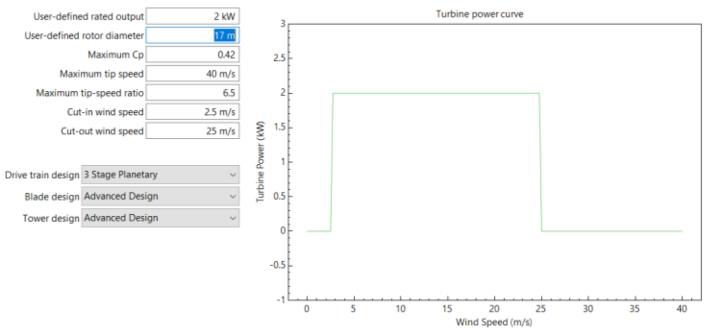


Figure 51. Rotor diameter 17m

Obviously, this is a turbine model defined manually, selecting the parameters needed adapted to the needs required, but this is not a turbine that can be found at the market in a commercialized mode, as it is only a facility that *SAM Energy* software gives.

Going forward with the simulation, first is needed to show the wind speed which is going to be working with. In the following Figure 52, it can be seen the wind speed distribution in Spain and the turbine response according to the wind speed that is receiving on Table 14.

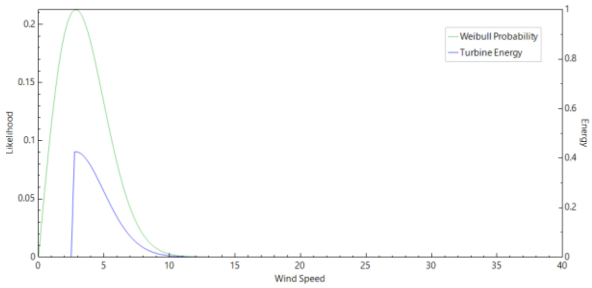


Figure 52. Wind speed distribution

Wind Speed (m/s)	Turbine Output (kW)
0	0
0.25	0
0.5	0
0.75	0
1	0
1.25	0
1.5	0
1.75	0
2	0
2.25	0

Wind Speed (m/s)	Turbine Output (kW)
2.5	0
2.75	2
3	2
3.25	2
3.5	2
3.75	2
4	2
4.25	2
4.5	2
4.75	2

Table 14. Wind turbine operating range

As shown, it is a distribution centered on 3.57 m/s with a Weibull factor of 2 [26]. As seen on the table on the right, this turbine has the cut-in wind speed at 2.75 m/s which means that it is starting to generate energy at this speed and, not only this but as well means that is giving directly 2kW of power at this speed. So, with the wind speed available at Barcelona and with this turbine set up, it is possible to generate a great amount of energy.

Metric	Value
Annual energy (year 1)	11,458 kWh
Capacity factor (year 1)	65.4%
Levelized COE (nominal)	20.03 ¢/kWh
Levelized COE (real)	15.99 ¢/kWh
Electricity bill without system (year 1)	$1,384
Electricity bill with system (year 1)	$52
Net savings with system (year 1)	$1,332
Net present value	$-5,952
Simple payback period	17.0 years
Discounted payback period	NaN
Net capital cost	$23,906
Equity	$9,562
Debt	$14,344

Table 15. Energy summary rotor diameter 17m

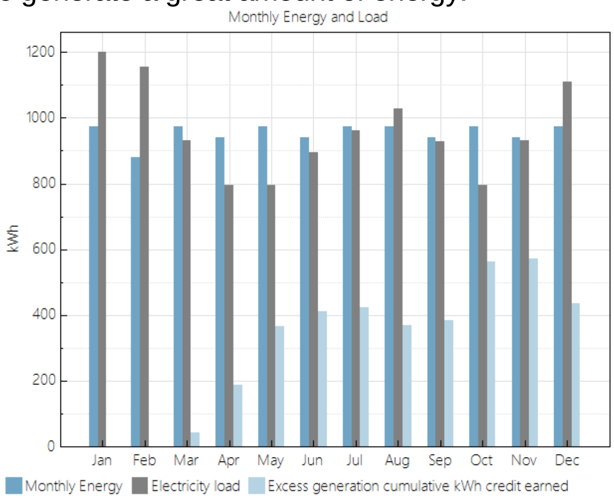


Chart 17. Demand coverage rotor diameter 17m

Once all these parameters are clear and introduced into the simulator, the result obtained are the ones shown on the Table 15 above. As shown on the bars Chart 17 on the right, the demand coverage is quite good as it is achieving the value of 96.4% of coverage including excess of energy generated at the end of the year, which means that this energy can be supplied to the grid and have an economic reward in return.

However, as mentioned before, this is an idyllic situation as this turbine that has been used in the simulation is it not possible to find in the market because the parameters have been adjusted accordingly.

Besides, exists a connection between the rotor diameter and the power that the turbine can provide to wind systems. Below, on the Figure 53, can be seen this relation between diameter and power.

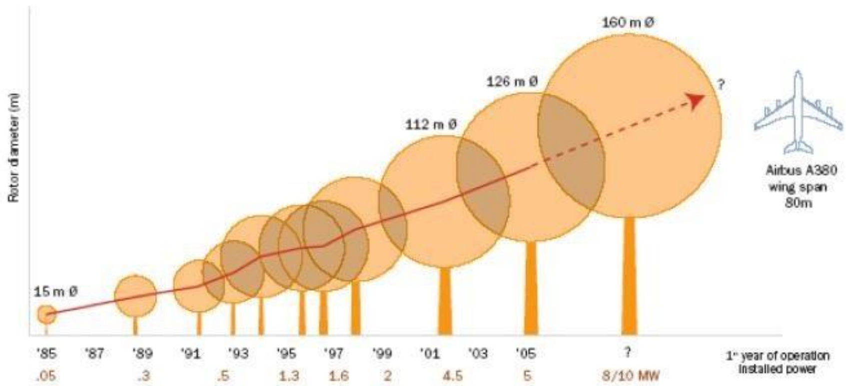


Figure 53. Rotor diameter vs turbines nominal power

As shown, in order to give an example, the smallest rotor diameter shown on the picture is 15 m which is related with a wind turbine of 50 kW power. So, in the example explained before it has been used 17 m diameter for a 2 kW power turbine, so that would mean that the turbine is not fully used enough. The main reason why it has not been used the entire potential of the turbine it is due to its economic impact on the overall results (the cost per kW installed was increasing the price of the investment).

4.2.1.2 Designs comparison

All the conclusions explained at the previous section, have been developed after trying to simulate this demand profile with several turbines available on the market and with the wind speed available at the region of study.

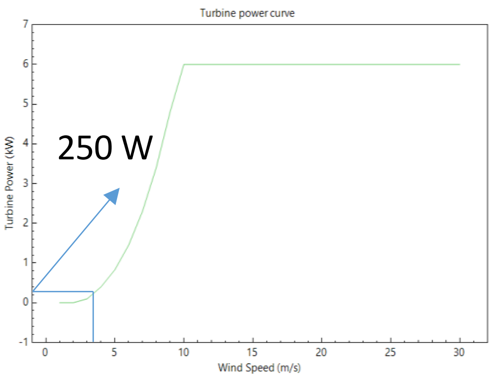


Figure 54. Turbine power curve 6kW

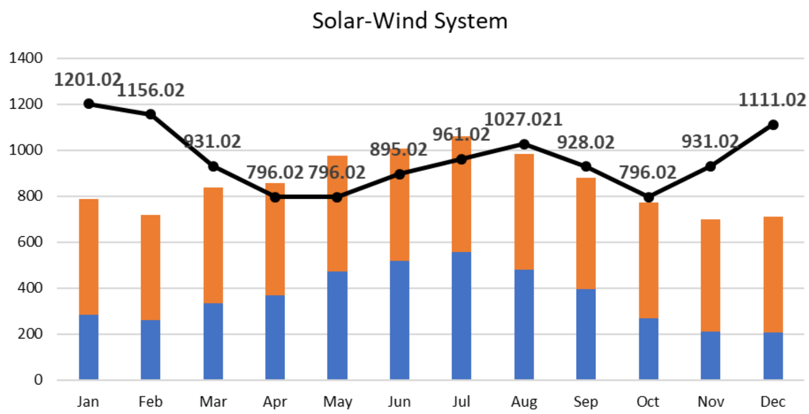


Chart 18. Solar and wind system energy generation 6 kW wind turbine

As shown on the Figure 54 above, on the left, it is possible to see the power curve for a 6 kW power turbine. The curve starts to grow up at 6 – 7 m/s wind speed approximately and the maximum power that this turbine can provide to the system with the 3.57 m/s average wind speed available in Barcelona is only 250 W.

As it is reflected on the Chart 18 on the right, the orange bars show the energy produced by the wind system, altogether with the solar system production which are the blue bars. The black trendline is showing the demand profile for a single-family household. As it can be seen, the demand coverage it not enough with this configuration as it is roughly an 87% of coverage.

Only at the months of April, May, June and July the demand is fully covered, but still with both systems, wind and solar, is possible to have a renewable house in a great percentage, which implicates a huge reduction on the dependency of the grid.

However, instead of using this turbine, and using the one presented before (the one that has been manually adjusted to the requirements) the results can change positively, as shown on Figure 55 and Chart 19 below.

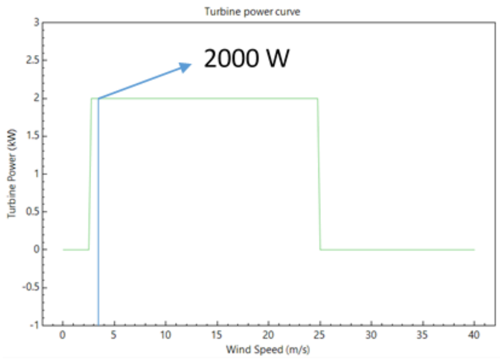


Figure 55. Turbine power curve 2 kW

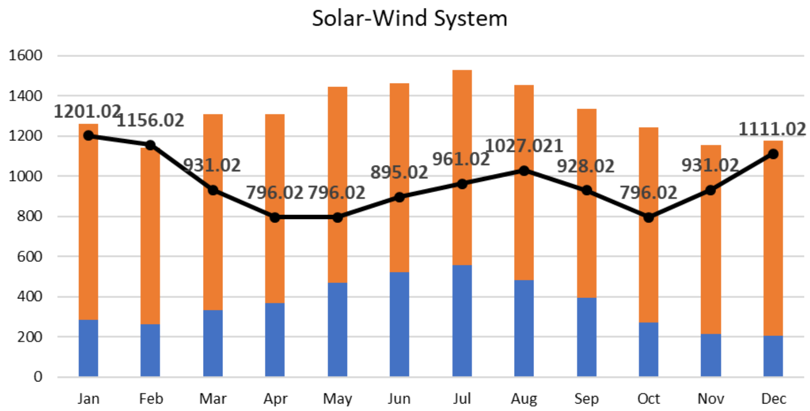


Chart 19. Solar and wind system energy generation 2 kW wind turbine

As it can be seen, with this turbine and with wind and solar systems working altogether, the demand profile for this single-family house is totally covered, even producing excess of energy that can be sold to the grid.

However, this situation is just a simulation and would be difficult to carry it out in a real case as this turbine cannot be find in the market. Besides, the wind speed available at the region of Barcelona is not that high as it could be in other regions and this is an important factor that prevents to produce high amounts of energy from this resource.

Due to that, as mentioned before on the preface section on this work, the government of Barcelona has calculated via simulation the small-scale wind project that could be done in the city and the energy that could be produce yearly (144,000 kWh/year).

Despite this situation, there are other alternatives of producing energy that would suit better but the economical side should be considered and revised as well because it may increase compared with the previous cases and would be needed to adjust it to the budget available.

4.2.2 Offshore turbines

Those other alternatives that have been mentioned before are the offshore turbines. Offshore wind energy is the use of wind farms constructed in bodies of water, usually in the ocean on the continental shelf, to harvest wind energy to generate electricity [27].

With this alternative, higher wind speeds are available offshore compared to on land (onshore turbines), so offshore wind power's electricity generation can be higher per amount of capacity installed.

In order to install an offshore wind farm, first is needed to check which is the wind speed average that can be taken in order to produce energy. As it can be seen at the Figure 56 below, thanks to the information provided by real-time and forecasting maps *Windfinder* [ref], it is possible to see how the wind is behaving in the Mediterranean coasts close to the Spanish country.

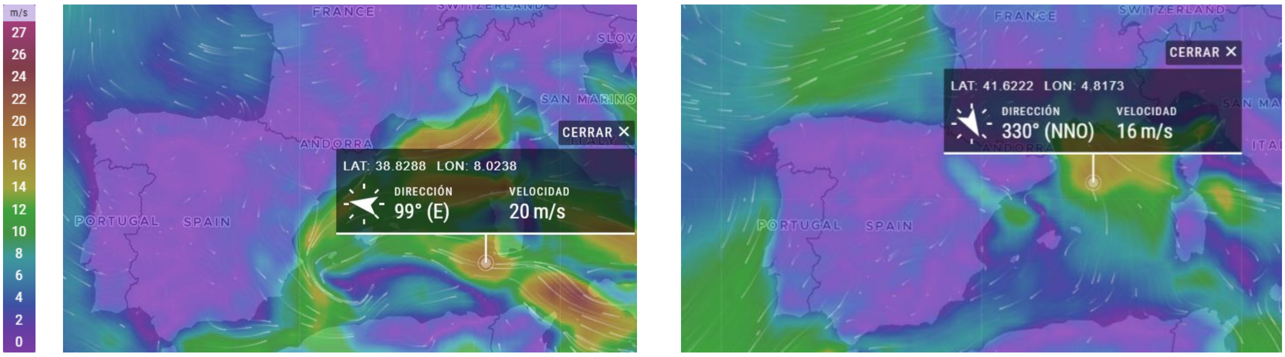


Figure 56. Wind speed offshore Mediterranean Sea

As shown, the wind speed varies between 15 – 20 m/s, which a great improvement if it is compared with the on-land wind speed (3 – 4 m/s) and which will allow the wind energy system to produce more energy and more efficiently. As in this zone it is possible to find a wind speed of 17 m/s in average, it has been decided to carry out a study with offshore turbines and see if it is feasible and worth it in terms of energy production.

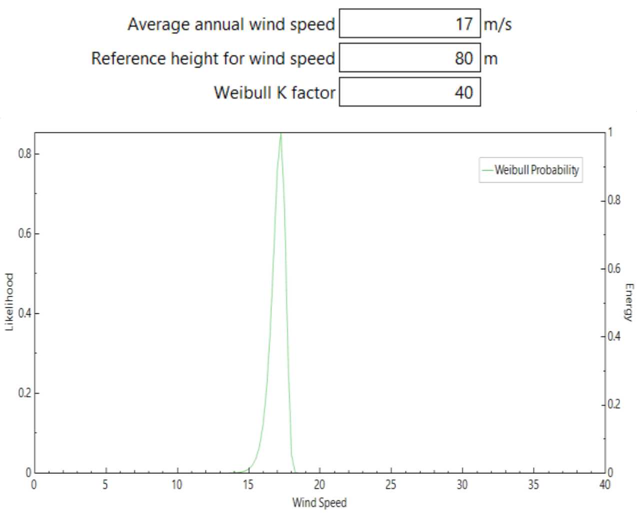


Figure 587. Average wind speed offshore

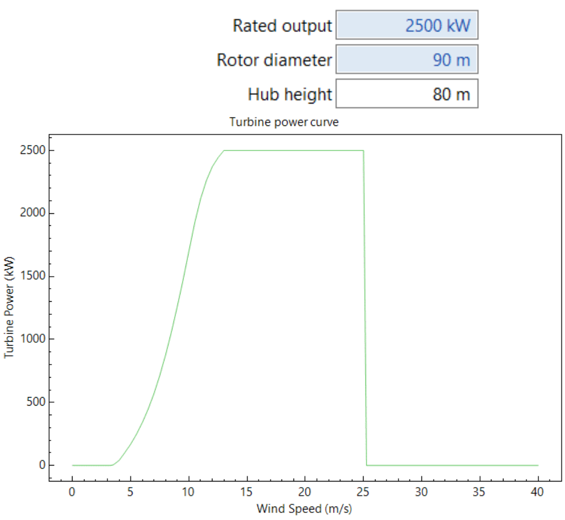


Figure 578. Turbine power curve 2500 kW

As the Figure 57, on the left, reveals, the simulation has been done with an average wind speed of 17 m/s with a Weibull K factor of 40, which means that the speed does not have a wide range of variation, in order to extract wind speeds from 15 m/s until 18 m/s, measuring the wind at 80 meters of height.

The turbine used for this simulation, as shown on the Figure 58 on the right side, it is a 2500 kW power turbine with a rotor diameter of 90 m and which model is *Nordex N90 – 2500 HS* which datasheet for further information can be found at the Annex. As shown on the figure, the turbine has a cut-in wind speed of 3.5 m/s and a cut-off wind speed of 25 m/s in order to automatically stop running in case of emergency.

On the Figure 59, below, it can be found the map of the Spanish country and the Mediterranean Sea. In purple, are marked the pieces of land where would be worth to install the offshore wind farm with a total extension of 107.18 km^2.

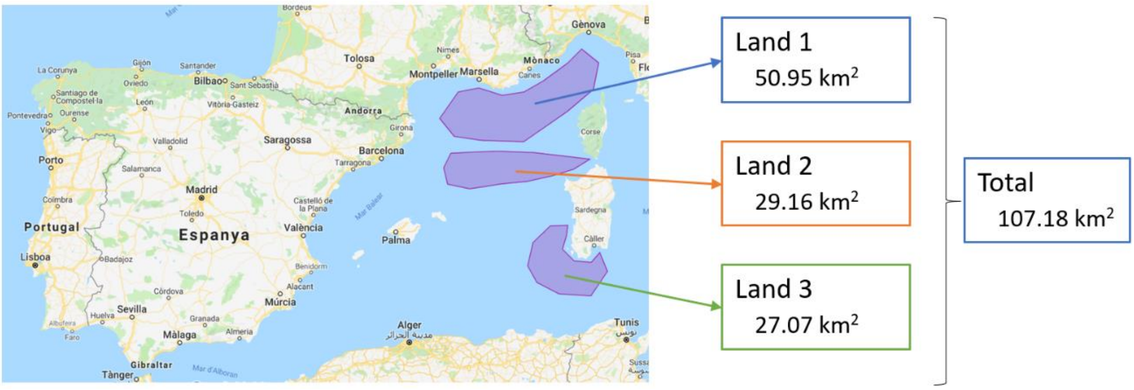


Figure 59. Mediterranean Sea wind fields

With this set up, it has been proceeded to do two different simulations, the first one with the average wind speed of 17 m/s and a farm size of 550 MW (220 offshore wind turbines). Below those results can be found.

Metric	Value
Annual energy (year 1)	4,817,999,360 kWh
Capacity factor (year 1)	100.0%
Levelized COE (nominal)	2.84 ¢/kWh
Levelized COE (real)	2.26 ¢/kWh
Electricity bill without system (year 1)	$819,994,624
Electricity bill with system (year 1)	$241,833,984
Net savings with system (year 1)	$578,160,640
Net present value	$3,764,338,944
Simple payback period	4.0 years
Discounted payback period	4.8 years
Net capital cost	$2,504,150,016
Equity	$0
Debt	$2,504,150,016

Table 16. Energy summary 17 m/s wind speed

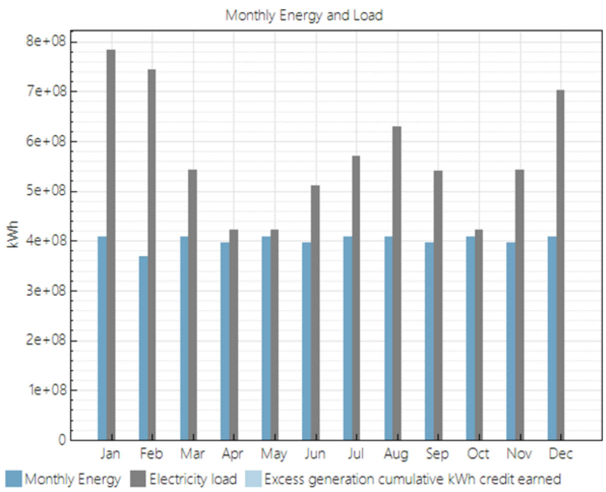
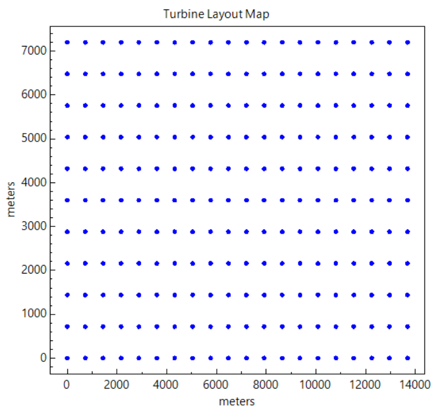


Chart 20. Demand coverage 17 m/s wind speeds

Continuing with the analysis for the city of Barcelona (considering the unitary demand profiles for the multi-family and single-family homes, together with the number of the different types of dwellings), it can be seen at the Chart 20, on the right, that demand coverage with this system is around a 73% which leads to think that combining this model with another renewable energy production system it could be possible to achieve the complete disconnection from the grid for the whole city of Barcelona.

Besides, on the Table 16, on the left side, the annual energy production is around 4,817 GWh and the *NPV* is positive and its value is $ 3,764 M with a payback of 4 years which is interesting for the investors (Barcelona's government). Regarding the land space available and the wind farm size needed, this wind farm is the one as follows (Figure 60).



$$13{,}680\ m \cdot 7{,}200\ m$$

$$\mathbf{98.5\ km^2}$$

Figure 60. Turbine layout map 220 turbines

As shown above, the area needed in order to build this wind farm is 98.5 km^2 which is smaller than the area available, 107.18 km^2, which means that the project would be feasible as the all the wind turbines could be allocated there.

On the following figure shown below, Figure 61 it can be seen the hourly distribution of the energy supply throughout an entire day (figure on the left) and the month of May (figure on the right). The wind energy supply is irregular, and it is not depending on the day or night time, because including the night, the wind can be still running the blades of the turbine so that energy can be produced during the night hours and supplied during the day (orange area).

Moreover, as it can be seen, the dependency from the grid is still latent (blue area) which means that the complete disconnection from the grid is not possible only with the implementation of this wind system.

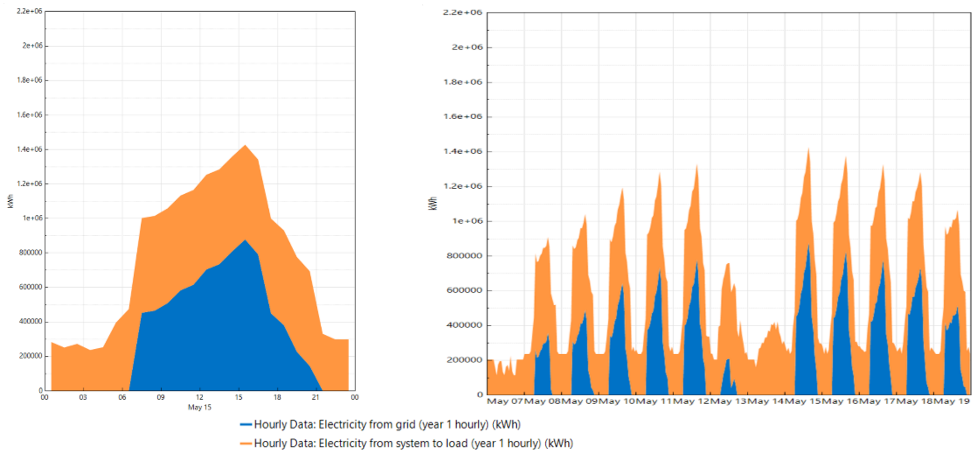


Figure 61. Hourly power distribution Barcelona wind offshore system

But the simulation it is not ending at this stage as, out of curiosity, it has been executed another simulation but this time with the maximum wind speed available in this region, in order to know what the percentage of demand coverage would be in case the wind would be blowing at its maximum value.

For that, it has been introduced the same value as before, only changing the wind speed to 20 m/s, with the same wind turbine model. The only difference is that this time the wind farm it is larger than before (the maximum value that *SAM Energy* allows to simulate).

Metric	Value
Annual energy (year 1)	6,131,999,744 kWh
Capacity factor (year 1)	100.0%
Levelized COE (nominal)	2.84 ¢/kWh
Levelized COE (real)	2.26 ¢/kWh
Electricity bill without system (year 1)	$819,994,624
Electricity bill with system (year 1)	$84,153,904
Net savings with system (year 1)	$735,840,704
Net present value	$4,790,976,000
Simple payback period	4.0 years
Discounted payback period	4.8 years
Net capital cost	$3,187,100,160
Equity	$0
Debt	$3,187,100,160

Table 17. Energy summary 20 m/s wind speed

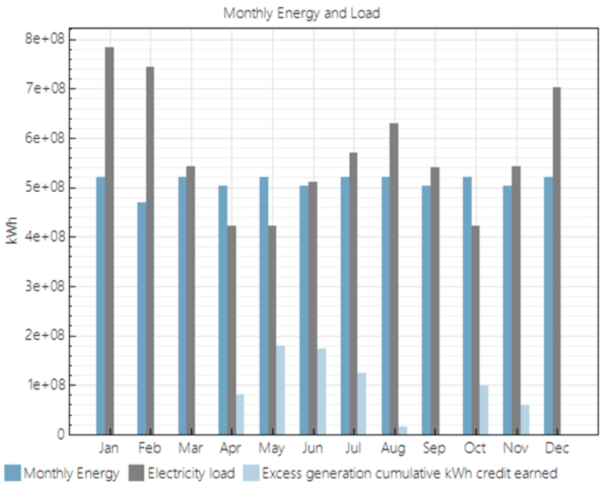


Chart 21. Demand coverage 20 m/s wind speeds

As it can be seen on Chart 21 above, the demand coverage this time is around a 94% but without excess generation at the end of the year (even it can be noticed that the last month of the year is not fully covered by the wind system and would be needed to ask for energy supply to the grid).

This time, the annual energy production is 6,131 GWh, a 17% more than the previous case and, as well, the *NPV* value is $ 4,790M which is much greater than the last case. However, it is possible to see that the payback period is the same as the previous analysis, which would mean that the investment is even better than the previous case because the *NPV* is greater, but the time needed to recover the investment is the same.

But in this case, the area needed is 158.1 km^2 which is greater than the piece of land available in order to build the windfarm.

This example has the stronger point of demand coverage, which is that almost all Barcelona's energy demand can be covered with this wind farm, but at the same time it has the weaker point of the lack of space in order to build it. Besides, it needs to be considered that wind energy is not very regular during the year and these results may vary when implementing the system in real cases.

This is the reason why there is the need of another back-up system in order not to run out of energy supply (solar system) or the continuous connection to the grid.

4.3 Biomass system

Previously on the preface section, it has been explained that the city of Barcelona has a wide range of biomass resources, mainly forest stocks, which can be burned and used in order to produce energy from them.

In fact, all the resources that the city has, can be found at the following Table 18 below, classified by municipality alongside with the energy that could be produced.

Municipality	Forest Stocks [t 30% WB]	Energy produced [kWh/t 30% WB]
Montacada i Reixac	10,544.77	3,207,758.61
Barberà del Vallès	899.98	291,966.20
Castellbisbal	9,437.61	2,244,752.09
Sant Cugat del Vallès	37,688.95	12,870,000.10
Badia del Vallès	7.65	1,846.63
Cerdanyola del Vallès	33,338.21	9,203,359.73
Ripollet	74.34	21,940.41
Tiana	2,142.44	576,307.25
Badalona	5,092.39	1,353,983.22
Montgat	511.81	122,616.99
Santa Coloma de Gramanet	1,669.91	444,842.56
Sant Andreu de la Barca	3,545.52	838,247.63
Papiol	7,073.81	1,711,814.44
Molins de Rei	20,593.72	5,323,068.14
Corbera de Llobregat	18,540.95	5,196,800.95
Pallejà	8,111.07	1,887,529.21
Sant Adrià del Besòs	-	-
Palma de Cervellé	8,569.03	1,981,343.51
Sant Feliu de Llobregat	7,714.39	8,721,274.29
Cervelló	31,649.23	1,234,519.75
Sant Vicenç dels Horts	5,006.25	1,141,743.00
Sant Just Desvern	3,517.66	21,079.83
Esplugues de Llobregat	92.41	903,083.47
Santa Coloma de Cervellé	3,602.96	4,483.86
Hospitalet de Llobregat	19.66	2,333.37
Sant Joan Despí	10.23	4,908,413.01
Torrelles de Llobregat	18,949.33	479.77
Sant Boi de Llobregat	2.10	1,106,359.40
Begues	4,023.41	7,290,442.19
Sant Climent de Llobregat	19,409.84	3,146,356.06
Prat de Llobregat	11,096.43	576,656.34
Viladecans	2,428.46	889,844.11
Barcelona	3,558.42	8,466,249.17
Gavà	15,028.90	4,125,137.87
Castelldefels	3,975.33	915,937.30
Total	**297,927.17**	**90,732,570.46**

Table 18. Biomass forest stocks available in Barcelona

As the numbers reflect, there is a total of **297,927.17 tones** 30% Wet Base (it means that the matter has a 30% of humidity in the forest stocks) available in order to be processed in biomass plants (as the ones already existing around the Spanish country) and converted to usable energy to be provided to the city.

All these tones, as the table shows, can be producing in a yearly basis around **90.73 GWh**. Even though this amount of energy, compared with the city's demand that it has been shown before, it is not that high, it can be used for small appliances or even for a back-up source of energy (storing the energy properly) for a late supply whenever it is needed.

As shown below on the Table 19 below (on the left side), it can be seen the energy production with the resources available and the *NPV* which is positive and the payback of 5.2 years which is not that long.

Metric	Value
Annual energy (year 1)	90,732,592 kWh
Annual biomass usage (year 1)	70,804 dry tons/yr
Capacity factor (year 1)	95.0%
Levelized COE (nominal)	8.97 ¢/kWh
Levelized COE (real)	7.12 ¢/kWh
Electricity bill without system (year 1)	$886,108,416
Electricity bill with system (year 1)	$874,012,160
Net savings with system (year 1)	$12,096,256
Net present value	$27,231,432
Simple payback period	5.2 years
Discounted payback period	6.8 years
Net capital cost	$40,939,008
Equity	$20,469,504
Debt	$20,469,504

Table 19. Energy summary biomass case

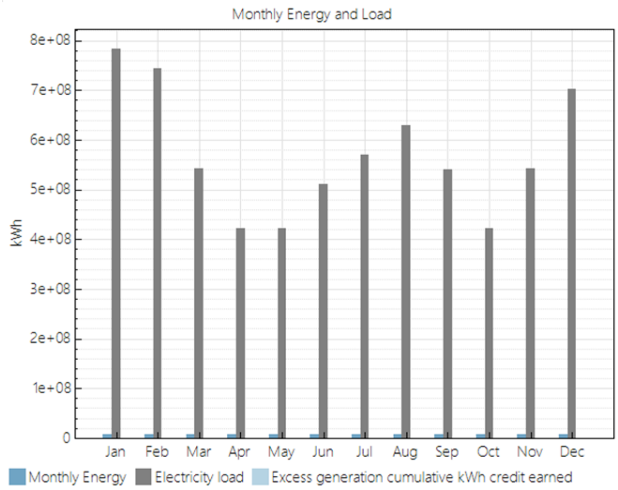


Chart 22. Demand coverage biomass case

Despite the numbers say that the investment would be worth, looking to Chart 22 on the right, it can be appreciated that the demand coverage is almost non-existent.

As matter of fact, it is only covering around a 1.41% of the whole demand profile of the city. Compared with this demand, it is impossible to consider biomass energy as a main source of energy supply.

Besides, at the Figure 62 below, it can be seen the energy production and distribution from the biomass resource and the connection to the grid.

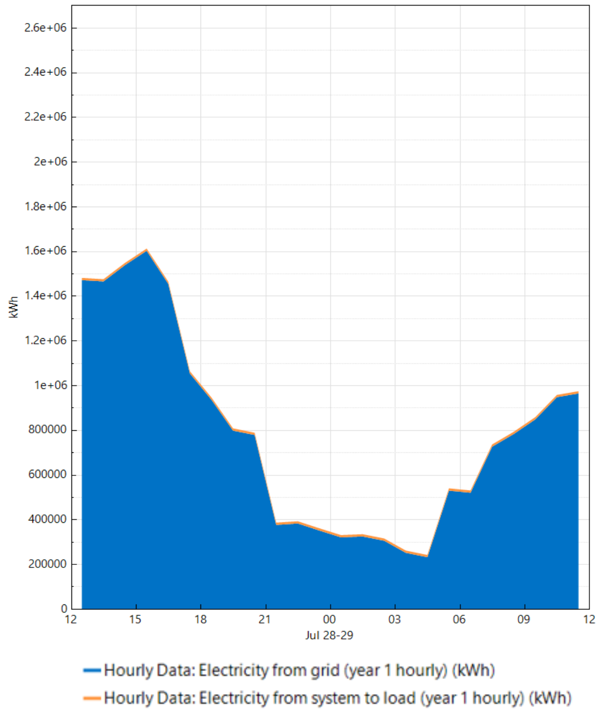


Figure 62. Hourly power distribution biomass case

As shown, the orange area (which is almost non-existent) is the one that shows the energy coming from the biomass system. As it can be appreciated it is almost nothing compared with the energy supplied from the grid (blue area) which is occupying all the area, so that, basically all the energy provided is coming from the grid.

For those reasons explained before, the option of biomass energy production it is not a good option when it comes to a large amount of energy demanded as it is the case of the whole city of Barcelona. Due to that, that kind of systems are not going to be considered in the last stage of analysis that are going to be proceeded and explained later in this work.

However, it is interesting the potential that the city has in terms of energy production from the biomass resources and thus, it can be taken advantage of this knowledge and use this energy for smaller purposes or profiles of demand.

4.4 Barcelona energy model

In this section is going to be modelled an energy model for different degrees of demand coverage for the whole city of Barcelona. There are going to be taken as a reference the numbers calculated before for multi-family and single-family households, as well as, the same models for panels and inverters in the solar PV systems cases and the same wind turbines in the wind systems.

For obvious reasons, it has been decided to discard the biomass option, as it has been seen and analysed before, the results were not as good and enough as expected for the demand profile of study. However, and as mentioned before, could be an alternative to consider in case the demand reaches some peaks that need to be supplied by some other sources of energy and avoiding the feed from the grid.

As mentioned at the section *2.2.1 Energy distribution* the budget that Barcelona predicted for the year 2020 in order to reach the 21% of renewable energy supply at the city was, among other values, 8,433.4 M€ for solar PV systems and 5,093 M€ for wind energy farms.

What is going to be done in the following sections is trying to show different demand coverage by different set ups, mixing solar and wind energy and trying to stick to the budget that the city has predicted.

4.4.1 Demand coverage of 50%

For the first case, is going to be simulated several alternatives to produce energy and try to cover the 50% of the demand. Although covering only the half of the needs of the city in terms of energy supply is not going to be enough to have a 100% renewable city, could be a great improvement as that would mean that some of the dwellings could be completely disconnected from the grid.

Besides, even if there are some dwellings left that cannot be completely disconnected from the grid, at least most of them are going to reduce its consumption of energy based on fossil fuels or other non-renewable energy sources, so that would be translated into a decrease of noxious emissions and an increase in the percentage of *renewability* of the city.

Solar PV system

For the first case of analysis, under the 50% demand coverage restriction, it has been simulated with panels model *SolarWorld Industries GmbH Sunmodule Protect SW 285 mono* and the inverter *Advanced Energy Industries: AE 1000NXC*.

The system design has an array size of 2,000 MW in direct current with 6,945,400 solar panels distributed in 173,635 strings in parallel of 40 modules each string. The azimuth angle is 165º and the tilt is 40º. The battery storage has not been considered.

As it can be seen at the below, it easily possible to reach the 50% of demand coverage with this setup. The system can be able to produce 3,228 GWh every year, in average, with a capacity factor of 18.4% as shown on the Table 20 on the left. Besides, can be appreciated that the electricity bill it has been reduced approximately a 41% (almost the half) thanks to the implementation of this system.

Metric	Value
Annual energy (year 1)	3,228,184,576 kWh
Capacity factor (year 1)	18.4%
Energy yield (year 1)	1,614 kWh/kW
Performance ratio (year 1)	0.84
Levelized COE (nominal)	8.36 ¢/kWh
Levelized COE (real)	6.67 ¢/kWh
Electricity bill without system (year 1)	$1,034,775,360
Electricity bill with system (year 1)	$612,461,760
Net savings with system (year 1)	$422,313,600
Net present value	$2,307,168,768
Simple payback period	9.6 years
Discounted payback period	16.9 years
Net capital cost	$5,391,553,024
Equity	$0
Debt	$5,391,553,024

Table 20. Energy summary solar PV 50% demand coverage

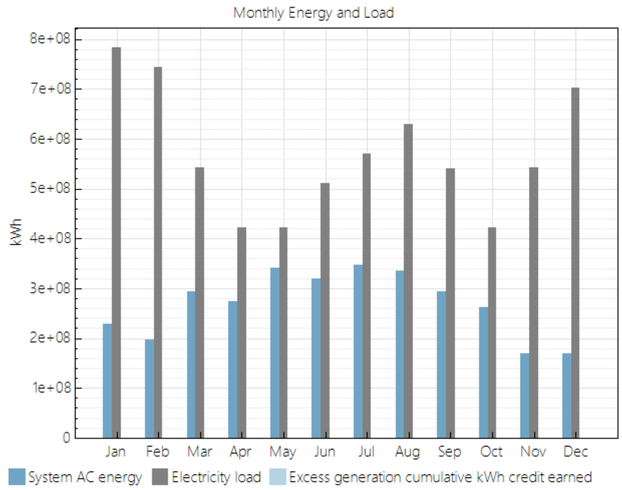


Chart 23. Demand coverage 50% solar PV

However, as shown on the Chart 23 on the right and it was previously expected, the demand coverage reached the 50.3% and, besides, any of the months during the year is completely covered so that, there is no excess of energy generated, fact that implies that there is no room for trade with the grid.

On the economical side, it is possible to see that the *NPV* is around $ 2,307M which means that the investment is worth and with a payback period of 9.6 years, which would be affordable and feasible for the government of Barcelona.

Besides, taking a look to the Figure 63 below, it is possible to see that the overall cost of the installation is $ 5,391.55 M and, if it is been compared with the initial budget for this project, which is 8,433.4 M€ ($ 9,528.19M), it is possible to see that could be affordable as the cost is inside the range expected for.

Total Installed Cost

Total installed cost	$ 5,391,553,024.00
Total installed cost per capacity	$ 2.70/Wdc

Figure 63. Total installed cost solar PV system 50% demand coverage

As shown, there is still budget available to increase the installed capacity of the installation and be able to produce more energy (which is going to be analysed later in this work). For further details on the cost distribution of the installation, check the Annex.

The Figure 64, on the left (May) and on the right (December) below, show the huge difference in terms of energy production and distribution hourly over the different seasons of the year, is it is not the same quantity produce in the month of May as it is in December

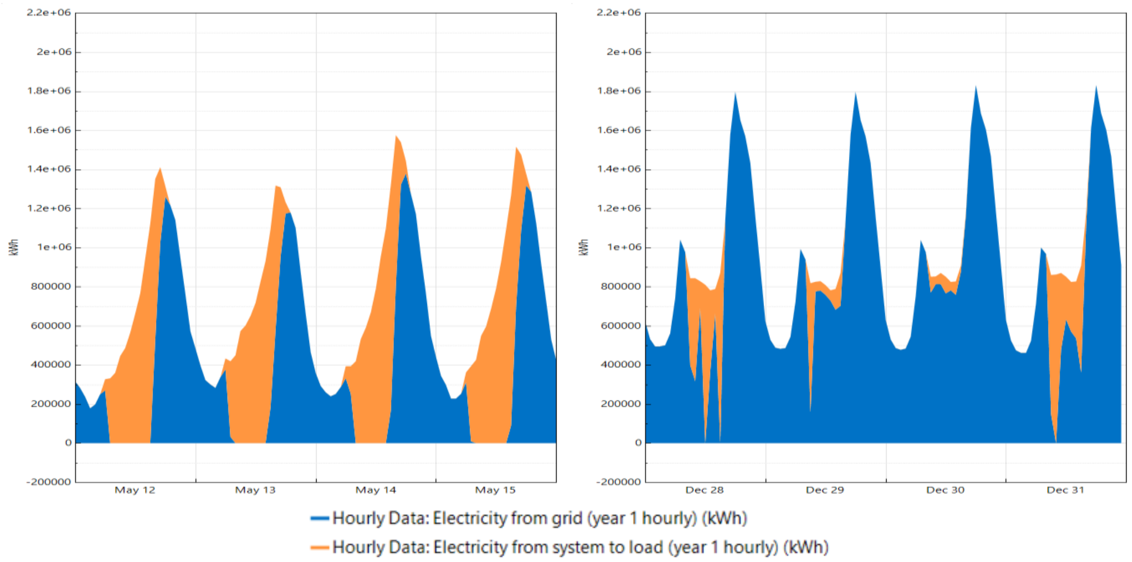


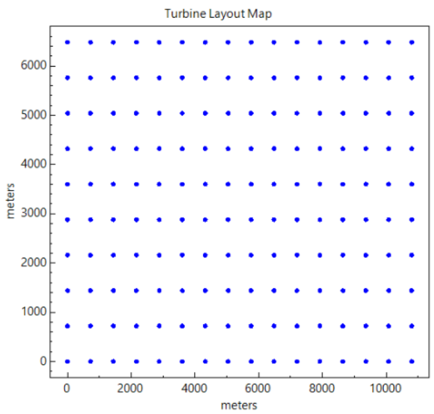
Figure 64. Hourly power distribution solar PV system 50% demand coverage

As shown, the dependency from the grid (blue area) on the right side, December, is huge as the one on the left side, May, due to the decrease on the irradiance at this season of the year.

Wind system

On the second case, it has been carried out the same analysis as the previous one. The demand profile is the same as previously and the wind turbine model used for this simulation is the same as mentioned before which model is *Nordex N90 2500 HS*.

Related with the wind speed used for the calculation, it is needed to comment that it has been tried previously with the on-shore wind speed, which value is 3.57 m/s and the result were not encouraging as it was not possible to cover the demand and besides, the *NPV* was negative. So, it has been decided to use the off-shore wind speed of 17 m/s.



$$6{,}480\,m \cdot 10{,}800\,m$$

$$\mathbf{69.98\ km^2}$$

Figure 65. Turbine layout map 50% demand coverage

As it can be seen on the previous Figure 65, the layout map for the wind farm needed in order to carry out this simulation is a total area of 69.98 km^2 which is expected to be build off-shore. As previously shown on the map's analysis with the *WindFinder* tool, there is enough space to fit 160 turbines that are needed for the fam with a total farm size installed of 400,000 kW.

Then after doing the simulation, the results are the ones shown below at Table 21 and Chart 24, where it is possible to see that the system can produce 3,505 GWh per year, alongside a capacity factor of 100% and being able to cover roughly the 53.5% of the city's demand.

Metric	Value
Annual energy (year 1)	3,503,999,488 kWh
Capacity factor (year 1)	100.0%
Levelized COE (nominal)	13.10 ¢/kWh
Levelized COE (real)	10.46 ¢/kWh
Electricity bill without system (year 1)	$819,993,792
Electricity bill with system (year 1)	$399,513,888
Net savings with system (year 1)	$420,479,904
Net present value	$516,276,896
Simple payback period	9.8 years
Discounted payback period	17.6 years
Net capital cost	$4,781,200,384
Equity	$1,912,480,128
Debt	$2,868,720,128

Table 21. Energy summary wind 50% demand coverage

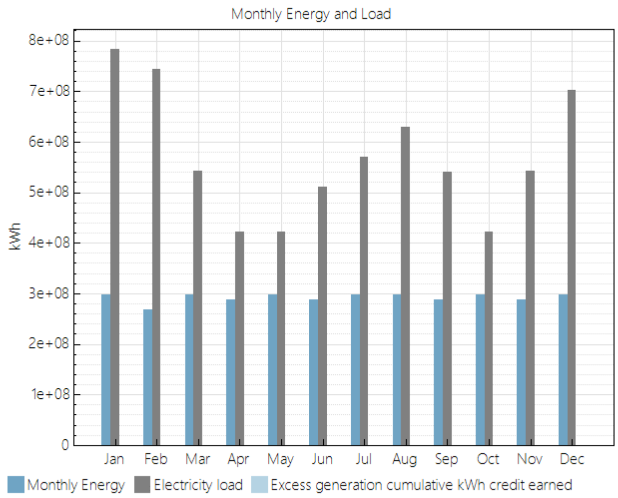


Chart 24. Demand coverage 50% wind

Looking at the economic side, it is shown that the investment is worth with a relatively reduced payback of 9.8 years and an *NPV* of $ 516M which means that the investment is going to bring benefits to the government.

Besides, on the Figure 66 below, there are classified the installation costs of the system, subdivided by two types of costs. The Turbine cost is subdivided by the cost per kW installed and the unitary price for each turbine acquisition which is needed to consider on the final costs. On the other hand, the balance of system costs include the majority of the pieces and installation costs and account for the majority of maintenance requirements [28].

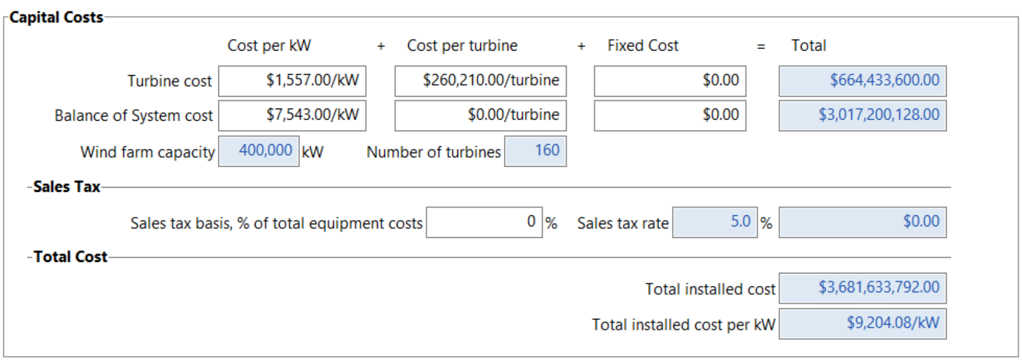


Figure 66. Total installed cost wind system 50% demand coverage

As shown above, considering the unitary acquisition price of this wind turbine of $ 260,210 [29], the total cost would be $ 3,681 M. If compared with the initial budget, which was $ 5,761.96 M (5,093 M€), it turns out that the investment is feasible and still, the government has more budget to invest in this technology.

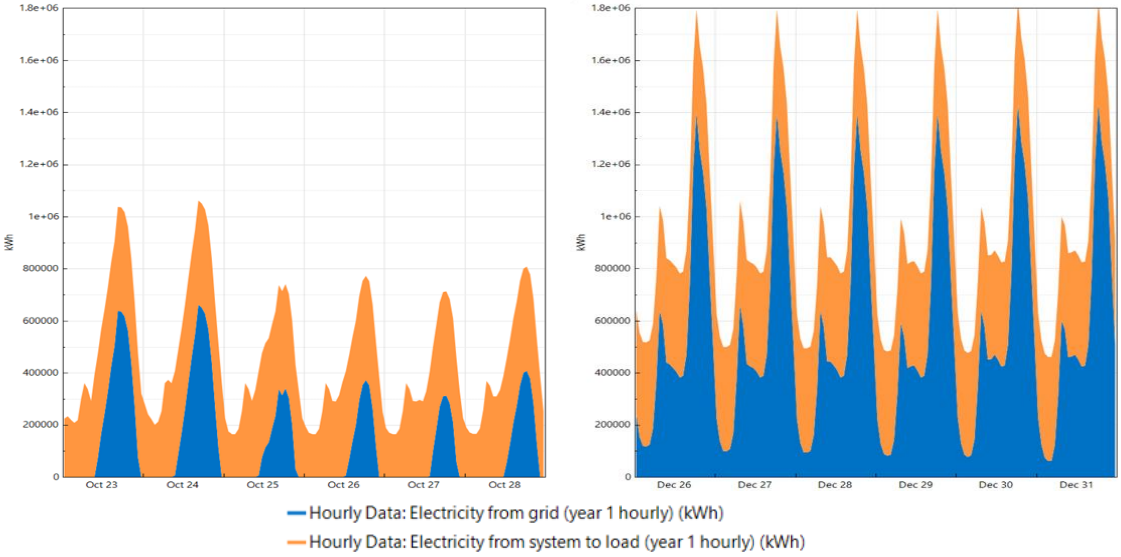


Figure 67. Hourly power distribution wind system 50% demand coverage

On Figure 67 it is captured the irregularity fact of the wind. As it can be appreciated the wind speed can vary throughout the year and so the peaks of energy generated from the wind, as in this example, the maximum peak in October is around 1 GWh meanwhile in December the maximum one is around 1.8 GWh, almost the double than in October.

This fact notes the importance of considering the variability of the wind and that all the results shown in this work are only approximations in order to have an idea of the amount of energy that could be generated with these systems.

Solar PV and Wind systems

In this section is going to be carried out the summary of the previous two subsections. The aim is to consolidate the results for both the solar and the wind systems in order to be able to provide the results on how much energy can be supplied in case the government of Barcelona decides to carry out the projects explained before.

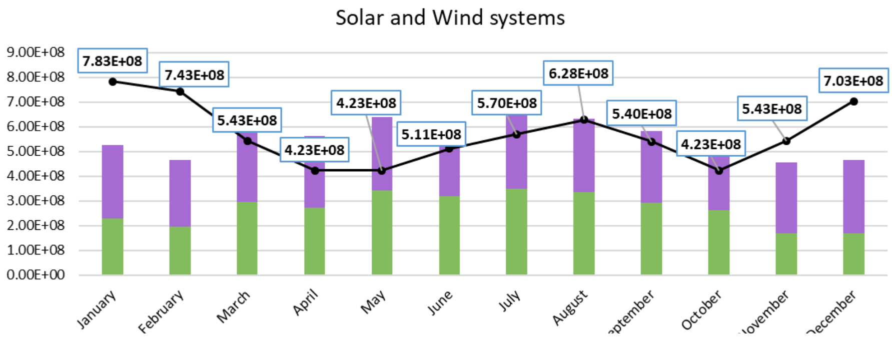


Chart 25. Solar and Wind system 50% demand coverage

As *SAM Energy* software does not have the option to simulate different system all-in-one it is needed to take the results separately from both simulations and calculate the final results using excel, as the Chart 25 shows.

In the graph, it is made clear that the highest peaks of demand, which take place in the coldest months of the year, from November to February (which they are currently all covered above the 60%), cannot be covered completely by both systems working in parallel covering the 50% of the demand separately, so that will mean that there is going to be needed the connection to the grid.

Could be another option to provide the system with batteries that could storage the excess of energy generated, as for instance, from March to October, both included, the amount of energy is over the one demanded, in small portions, and this overproduction could be supplied in those months were the lack of energy takes place. Even doing that, could not be enough for supply all the energy needed, so it will be recommendable to stay connected to the grid.

4.4.2 Demand coverage of 100%

In order to be able to see if there is any chance for the city of Barcelona to be disconnected completely from the grid, in this section there are going to be carried out the same series of simulations that were proceeded in the previous section but, this time, intending to provide 100% of demand coverage, first with the solar PV system, and later with the wind system.

After that, everything is going to be wrapped up, as done before and then provide the results for an idyllic situation. The reason why would be idyllic is because installing those systems being able to generate enough energy for the whole city by their own, would implicate a huge investment, which more than probably will be out of the budget available.

Solar PV system

Starting with the solar PV system, the whole set up is the same as the one done previously, the only thing that will change now is the number of panels installed and the array size.

Metric	Value
Annual energy (year 1)	12,105,705,472 kWh
Capacity factor (year 1)	18.4%
Energy yield (year 1)	1,614 kWh/kW
Performance ratio (year 1)	0.84
Levelized COE (nominal)	8.36 ¢/kWh
Levelized COE (real)	6.67 ¢/kWh
Electricity bill without system (year 1)	$1,034,775,360
Electricity bill with system (year 1)	$94,048,736
Net savings with system (year 1)	$940,726,656
Net present value	$1,691,750,912
Simple payback period	16.3 years
Discounted payback period	NaN
Net capital cost	$20,218,345,472
Equity	$0
Debt	$20,218,345,472

Table 22. Energy summary solar 100% fully covered

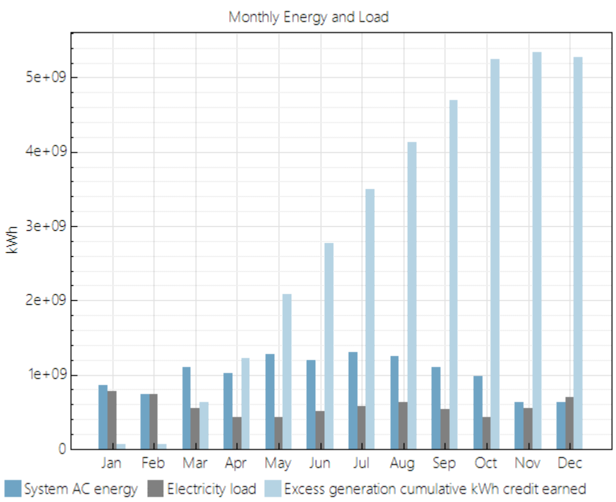


Chart 26. Demand coverage solar 100% fully covered

In this simulation there are needed a total amount of 26,045,280 panels, distributed in 651,132 strings in parallel of 40 modules each and with a total array size of 7.5 GW of direct current. As it can be seen on the Chart 26, on the right, the value of excess of energy produced is extremely huge compared with the demand needed by the end of the year, but this is the only way to cover the first months of January and February the first year.

Another alternative would be leave uncovered January and February of the first year (stay connected to the grid) and use the excess of energy generated at the end of the first year to provided it at those two months of the second year.

Metric	Value
Annual energy (year 1)	6,456,369,152 kWh
Capacity factor (year 1)	18.4%
Energy yield (year 1)	1,614 kWh/kW
Performance ratio (year 1)	0.84
Levelized COE (nominal)	8.36 ¢/kWh
Levelized COE (real)	6.67 ¢/kWh
Electricity bill without system (year 1)	$1,034,775,360
Electricity bill with system (year 1)	$308,132,704
Net savings with system (year 1)	$726,642,688
Net present value	$3,495,988,224
Simple payback period	11.1 years
Discounted payback period	23.1 years
Net capital cost	$10,783,106,048
Equity	$0
Debt	$10,783,106,048

Table 23. Energy summary solar 100% partially covered

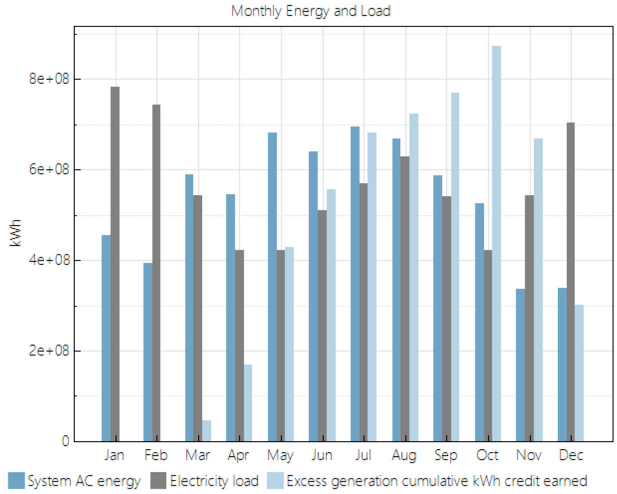


Chart 27. Demand coverage solar 100% partially covered

As shown on the Table 23 and Chart 27 above, with this energy production model the months of January and February would be covered the second year and so that, the cost of the whole project would be much cheaper than in the previous example. Despite the cost installation is a bit higher than the budget predicted, this is the approach is going to be considered later when mixing this technology with the wind energy too.

Wind system

In order to recreate the simulation done before but this time with wind energy, it has been proceeded under the following assumptions: 17 m/s wind speed offshore model and a wind farm size of 700,000 kW with 280 turbines. This setup is the maximum that *SAM Energy* can support and is the one which is going to proceed with from now on.

Metric	Value
Annual energy (year 1)	6,131,998,720 kWh
Capacity factor (year 1)	100.0%
Levelized COE (nominal)	11.77 ¢/kWh
Levelized COE (real)	9.40 ¢/kWh
Electricity bill without system (year 1)	$819,993,792
Electricity bill with system (year 1)	$84,154,120
Net savings with system (year 1)	$735,839,680
Net present value	$1,669,610,624
Simple payback period	8.3 years
Discounted payback period	12.8 years
Net capital cost	$6,442,858,496
Equity	$2,577,143,296
Debt	$3,865,715,200

Table 24. Energy summary wind 100% coverage

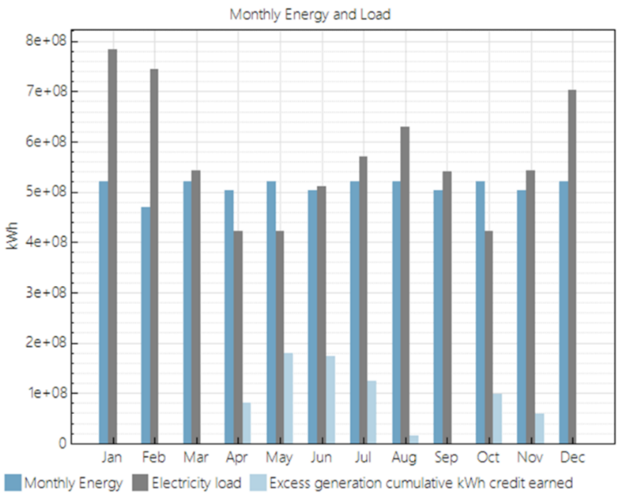


Chart 28. Demand coverage wind 100%

With this configuration, the maximum demand that can be provided with this wind system it is around the 91.1% of demand coverage. However, it can still be seen that there are some months that are uncovered, like the first three and the last one (December to March) which are the month of higher consumption, due to the heater performance in the winter season.

Besides, looking to the economical side, it is possible to see that the *NPV* is positive and the payback period is only 8.3 years. But there is one point that is not matching with the conditions that were established before: the total installation costs are over the budget that the government of Barcelona has for this technology. As it can be seen on the Figure 68 below, the total cost is $ 6,434M and the budget predicted for building wind energy project was $ 5,761.96 M.

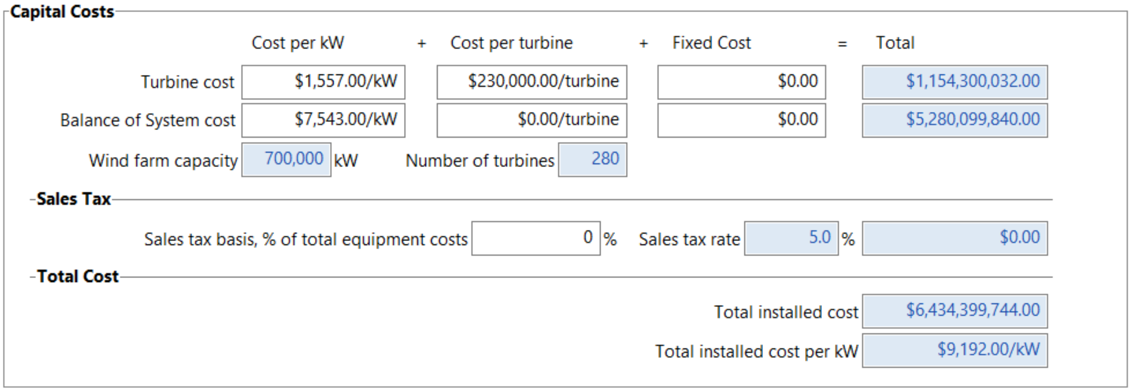


Figure 68. Total installed cost wind 100% coverage

In front of this situation there are only two alternatives left. On one hand could be considered the option of extend the budget that was predicted before in order to match with the costs of this installation. On the other hand, can be possible to build a smaller array size, with less turbines and, consequently, less energy generated, and demand covered, but adjusting the costs to the initial budget, as shown on the following Table 25 and Chart 29:

Metric	Value
Annual energy (year 1)	5,255,998,976 kWh
Capacity factor (year 1)	100.0%
Levelized COE (nominal)	11.76 ¢/kWh
Levelized COE (real)	9.39 ¢/kWh
Electricity bill without system (year 1)	$819,993,792
Electricity bill with system (year 1)	$189,274,096
Net savings with system (year 1)	$630,719,680
Net present value	$1,437,370,496
Simple payback period	8.3 years
Discounted payback period	12.8 years
Net capital cost	$5,515,200,000
Equity	$2,206,080,000
Debt	$3,309,120,000

Table 25. Energy summary wind system smaller array

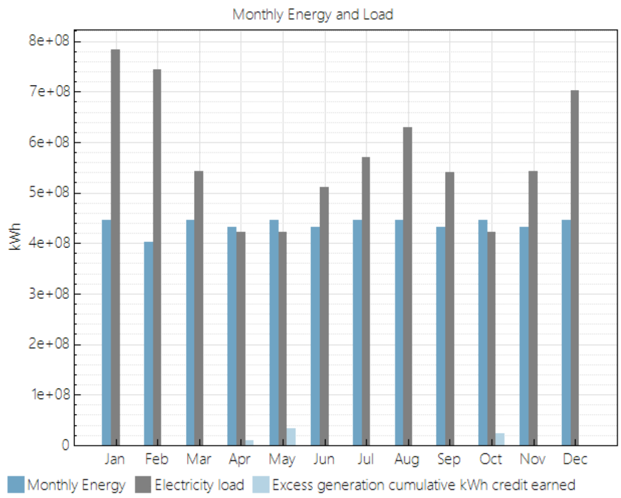


Chart 29. Demand coverage wind system smaller

With that configuration (240 turbines and 600,000 kW array size), the energy demand can be covered in a 79% and the installation costs would be $ 5,515.2 M, lower than the initial budget which was $ 5,761.96 M.

Solar PV and wind systems

After analysing both systems separately, solar PV and wind, in this section it has been carried out the simulation of 100% of demand coverage within the mix between those two renewable technologies.

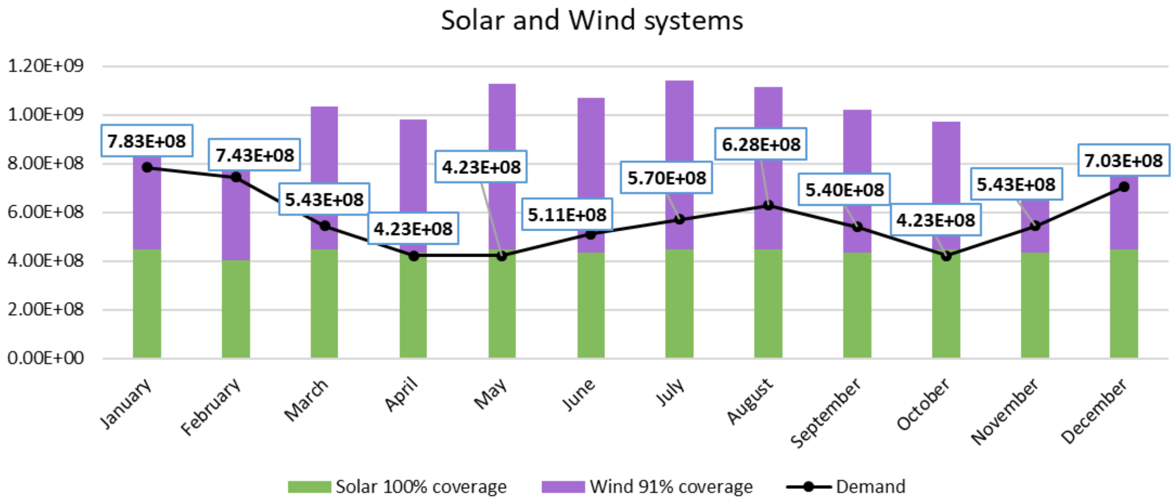


Chart 30. Solar and Wind system 100% demand coverage

As it can be seen on the Chart 30 above, all the months along the year are completely covered with the 100% coverage solar PV system and the 91% coverage wind system. Besides, the demand profile is not only fully covered but, as well, there is a huge excess of energy generation that can be whereas traded with the grid or stored in a battery storage system.

As mentioned before, this configuration exceeds the budget previewed by the government of Barcelona as the solar PV system would cost \$ 10,783.11 M and the wind system \$ 6,434 M which would turn out in a total amount of \$ 17,217.11 M, but this analysis it has been done with the aim of showing the capabilities and which would be the configuration of the renewable systems that the city could implement.

4.5 Comparative table

Below, in Table 26, it is shown the comparative between the alternatives presented alongside with the different demand coverages.

		Energy Demand (kWh/yr)	Energy Production (kWh/yr)	Cost (M$)	Budget (M$)
50%	Solar PV	6.83E+09	3.23E+09	5,392	9,528
	Wind		3.50E+09	3,681	5,762
	Solar PV + Wind		6.73E+09	9,073	15,290
100%	Solar PV		5.26E+09	10,783	9,528
	Wind		6.46E+09	6,434	5,762
	Solar PV + Wind		1.17E+10	17,217	15,290

Table 26. Comparative table between 50% and 100% coverages

As it can be seen, and as a summary, the best option to choose for the government of Barcelona would be the 100% demand coverage, even if the total installation cost of both systems is $ 1927 M above the budget, because the quantity expended it is not too far from what it was previously predicted and, thus, the demand of the city would be fully covered.

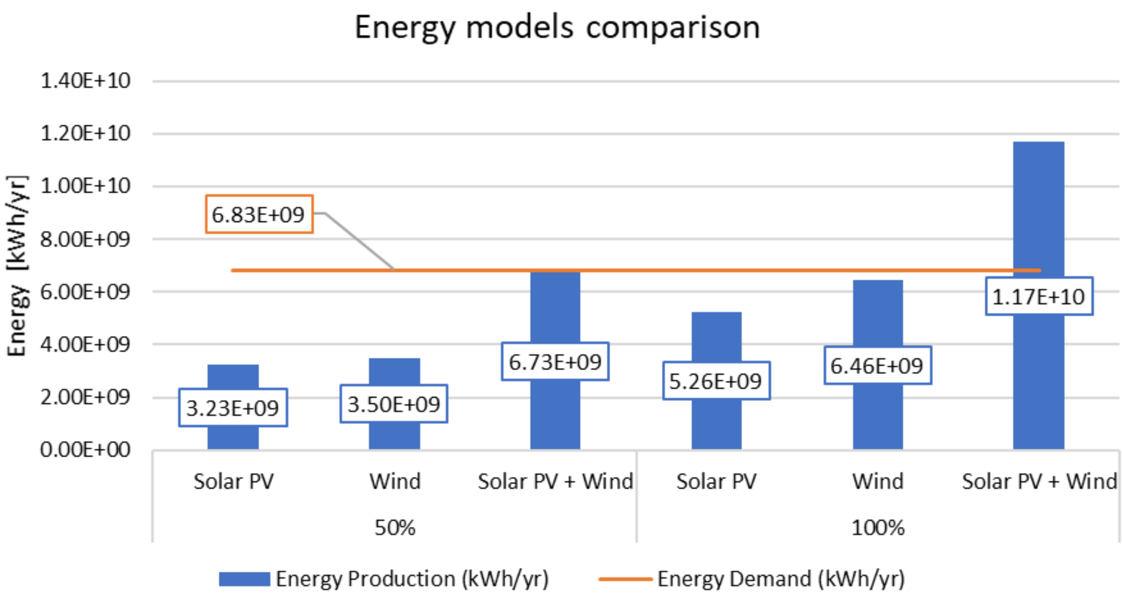


Chart 31. Energy models comparison versus Barcelona's demand profile

However, combining both energy systems with the 50% of demand coverage would be an affordable and eligible option that, although the demand is not fully covered (winter months, from November until February are uncovered), the rest of the year the energy produced is enough to cover all the city demand and, overall, the yearly energy produced is close to the energy demand value needed (see Chart 31 above) and, more important, the costs are inside the budget range that was predicted.

Those models could help the city to move into greener scenarios, self-producing energy and preventing from the production of harmful emissions for the environment. Even if it is not possible to be fully renewable, being able to produce around 60-70% of the energy demanded from renewable resources would help the city to produce energy in a cleaner way, being capable of self-supply and produce its own electricity.

All the charts and simulations above have been done with the help of the SAM Energy software alongside with its documentation and forums [30].

5 Execution of the project

5.1 Temporal horizon

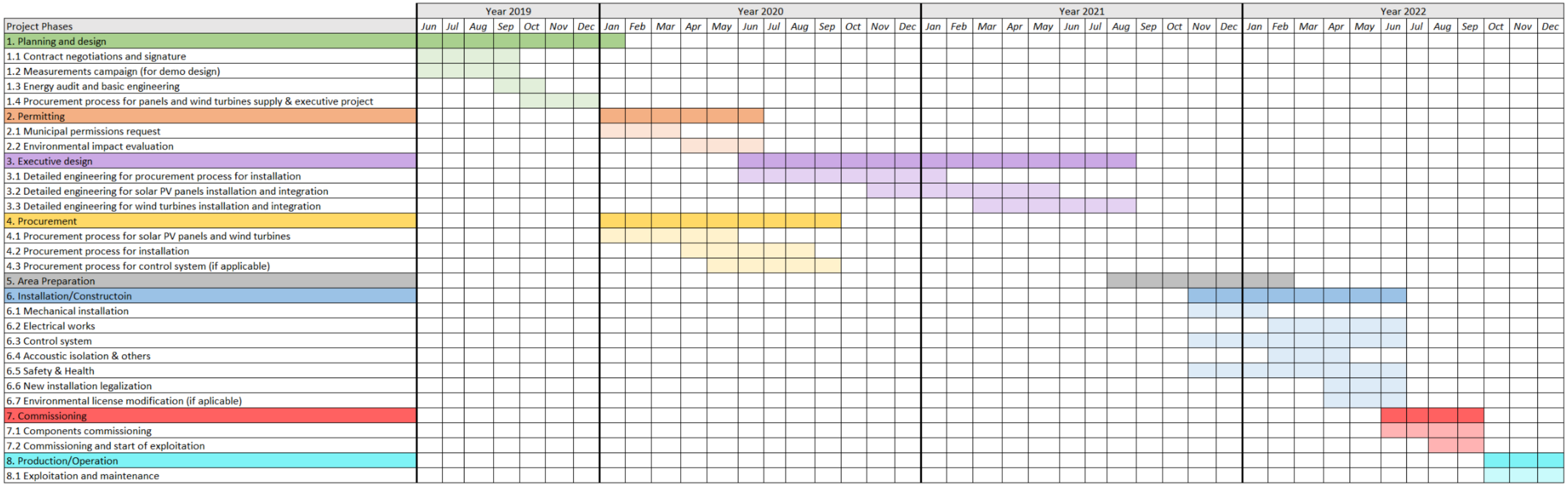


Figure 69. Phases of the project and temporal horizon

5.2 Economic study

STAGES	PHASES	Budget for every year in US dollars ($)													
		2019			2020				2021				2022		
1. Planning and design	1.1 Contract negotiations and signature	560	560												
	1.2 Measurements campaign (for demo design)	1120	1120												
	1.3 Energy audit and basic engineering		3360	3360											
	1.4 Procurement process for panels and wind turbines supply & executive project		5600	5600											
2. Permitting	2.1 Municipal permissions request			560	560	560									
	2.2 Environmental impact evaluation					560									
3. Executive design	3.1 Detailed engineering for procurement process for installation					6720	6720	6720							
	3.2 Detailed engineering for solar PV panels installation and integration						5E+09	5E+09							
	3.3 Detailed engineering for wind turbines installation and integration						3E+09	3E+09							
4. Procurement	4.1 Procurement process for solar PV panels and wind turbines			12320	12320										
	4.2 Procurement process for installation				1120	1120	1120								
	4.3 Procurement process for control system (if applicable)				1120	1120									
5. Area Preparation	5.1 Extension of structures							2240	2240						
6. Installation/Constructoin	6.1 Mechanical installation									2240					
	6.2 Electrical works										2240	2240			
	6.3 Control system									3360	3360	3360			
	6.4 Accoustic isolation & others										3360				
	6.5 Safety & Health									2240	2240	2240			
	6.6 New installation legalization										3360	3360			
	6.7 Environmental license modification (if aplicable)														
7. Commissioning	7.1 Components commissioning											2240	2240		
	7.2 Commissioning and start of exploitation												2240		
8. Production/Operation	8.1 Exploitation and maintenance													112	112
		1680	**10640**	**21840**	**15120**	**10080**	**9E+09**	**9E+09**	**2240**	**7840**	**14560**	**13440**	**4480**	**112**	**112**
		TOTAL = 17,217,118,944													

Figure 70. Detailed economic costs of the project

6 Conclusions

At this stage of the project there are going to be listed and explained the main conclusions extracted after analysing the energy model developed for the city of Barcelona.

Accordingly with the project objectives listed before at the beginning of this work, below are listed the conclusions extracted from:

- It has been possible to establish the picture of the city of Barcelona in terms of energy resources availability, emissions currently generated and new opportunities fields that could be checked and improved.
- It has been found that the main resources available in the city are the sun and the wind and it has been stated where can be located the projects that could be developed from these resources and quantified numerically the potential of them, including the energy that could be generated.
- Thankfully to the Renewable Energy Plan issued by the government of Barcelona it has been possible to know the funds that the city is able to invest in RES projects, so that, it has been possible to perform an economical and technical analysis.
- It has been successfully calculated the energy needs, both for single-family and multi-family dwellings. Besides, it has been extrapolated those unitary energy demand profiles to the entire city and surroundings needs.
- After being able to calculate the demand for every dwelling it has been performed and shown an energy demand profile standard model and it has been possible to show how to cover this demand with the different technologies available in the city, which are mainly solar and wind energy.
- It has been developed a complete simulation analysis with *SAM Energy* software which has allowed to preview the amount of energy generation depending on the inputs established alongside with the economical parameters and the technical data provided by this software which has helped to understand the behaviour of the systems studied under different scenarios.
- With the help of the software acquired, it has been possible to complete several analyses of the different technologies, such as solar, wind and biomass energy (even this last one has been discarded for the following analysis because its low efficiency). The results, both the technical (energy) and economical (costs, budget), have been compared and this has allowed to choose the best option according with the funds that were available. It has been defined as well the horizon of the project and its stages.

Furthermore, after an exhaustive study of Barcelona’s energy distribution, it has been verified that the city is still too much dependant on fossil fuels and other non-renewable energy resources. However, it has been found that has also a great potential of renewable energies and that the government is taking several actions in order to impulse them.

As commented before on the objectives, it has been accomplished the main purpose of the project which was performing an energy model and a way of analysing regions in order to let the reader understand how to make a completed energy analysis of any desired location.

Besides, this work has allowed the knowhow of potential and energy production calculation and analysis, which are the parameters that need to be considered and how they should be measured.

The main conclusion of this project is giving an overall perspective and a few detailed insights of how to promote the energy model that is running nowadays in the city. The main purpose would be helping the government (and not only Barcelona's one) to go forward on the several implementations of renewable energy production systems, in order to be able to save money, reduce CO_2 emissions and making smarter cities with a higher percentage of energy production coming from RES.

So, overall, it is being demonstrated in this work that increasing the renewable percentage of the city is something feasible and that is not too far from where they are, so this project is trying to encourage and help the government to use this information in order to improve Barcelona's way of producing energy.

6.1 Next steps

The future lines of this project would be:

- Make further analysis with different solar technologies such as CSP (which is a technology that Barcelona is betting for as well), as solar power is one of the main resources in Spain.
- Make a huge implementation such as done for Barcelona but this time for the whole Spanish country with distribution lines that could bring energy to those places where is not possible to produce it due to lack of resources.

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8 Annex

8.1 Solar PV map

In the calculations per piece of ground it has been considered the following calculation hypothesis:

- The useful area of generation for each plot, independent of the category, is taken as an average value, therefore, it is considered 85% of the map value
- The installable power is obtained from a coefficient of occupation of 70% of the useful surface (70% cover the distance between plates to avoid shadows).
- The module used in the simulation is 270 W and 2 m2
- The generated energy is calculated in average and with a value of 1,250 kWh / kWp·year.
- For the calculation of equivalences in the dwellings has been considered a total value of 2,300 electrical kWh.
- The calculation of the common areas has been considered based on the height of the building.
- The saving of greenhouse gas emissions has been calculated according to the displacement of combined cycles; This is equivalent to a specific value of 0.360 kgCO2eq / year
- In the price estimation has been considered a value of € 3.5 / kWp.
- The maintenance cost is € 30 / kWp·year
- The estimated economic savings are estimated at € 0.12 / kWh.

8.2 Wind map (Onshore)

The considerations regarding the calculations are:

- The small-scale wind map provides less data than solar maps, since there is no such information available.
- Depending on the area, the average energy value that could be obtained has been calculated with a 1 kW type wind turbine.
- The energy obtained depends on the estimated wind regime in the area where the building is located, but no shielding between farms has been considered.
- The emission savings have been calculated based on the displacement of energy from combined cycle plants, that is, it has been considered a saving value of 0.360 kgCO2eq / year
- The useful area of generation for each plot, independent of the category, is taken as an average value, therefore, it is considered 85% of the map value

8.3 Example solar PV system 18 panel's report

System Advisor Model Report

Photovoltaic System	5.18 kW Nameplate	unknown, -
Residential	$2.70/W Installed Cost	41.39 N, 2.16 E GMT +1

Performance Model

Modules	
SolarWorld Industries GmbH Sunmodule Protect SW 285 ..	
Cell material	Mono-c-Si
Module area	1.68 m²
Module capacity	287.96 DC Watts
Quantity	18
Total capacity	5.18 DC kW
Total area	30 m²

Inverters	
SMA America: SB3800TL-US-22	
Unit capacity	3.850000 AC kW
Input voltage	100 - 480 VDC DC V
Quantity	1
Total capacity	3.85 AC kW
DC to AC Capacity Ratio	1.35
AC losses (%)	2.00

Array	
Strings	2
Modules per string	9
String voltage (DC V)	0.00
Tilt (deg from horizontal)	40.00
Azimuth (deg E of N)	165
Tracking	no
Backtracking	-
Self shading	no
Rotation limit (deg)	-
Shading	no
Snow	no
Soiling	yes
DC losses (%)	4.44

Performance Adjustments	
Availability/Curtailment	none
Degradation	0.500000 %/yr
Hourly or custom losses	none

Annual Results (in Year 1)	
GHI kWh/m²/day	4.50
POA kWh/m²/day	4.00
Net to inverter	8,640 DC kWh
Net to grid	8,130 AC kWh
Capacity factor	17.9
Performance ratio	0.81

Financial Model

Project Costs	
Total installed cost	$13,972
Salvage value	$0

Analysis Parameters	
Project life	25 years
Inflation rate	2.5%
Real discount rate	6.4%

Project Debt Parameters (Mortgage)	
Debt fraction	100%
Amount	$13,972
Term	25 years
Rate	5%

Tax and Insurance Rates	
Federal income tax	15 %/year
State income tax	7 %/year
Sales tax (% of indirect cost basis)	5%
Insurance (% of installed cost)	0.5 %/year
Property tax (% of assessed val.)	0 %/year

Incentives	
Federal ITC	30%

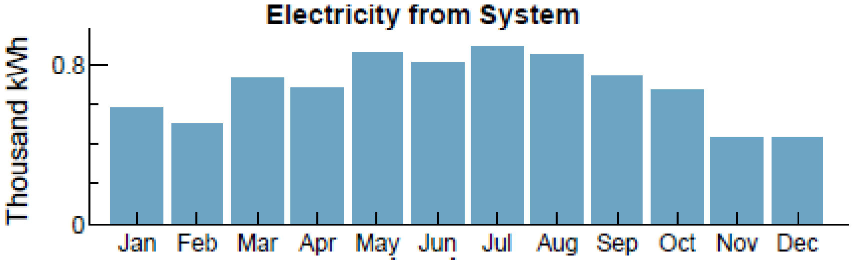
Electricity Demand and Rate Summary
Annual peak demand 3.2 kW
Annual total demand 11,529 kWh
Portland General Electric Co
Residential Time-Of-Use Service (Rate 7-TOU)
Fixed charge: $11.690000/month
Monthly excess with kWh rollover
Tiered TOU energy rates: 3 periods, 2 tiers

Results	
Nominal LCOE	8.5 cents/kWh
Net present value	$3,300
Payback period	12.5 years

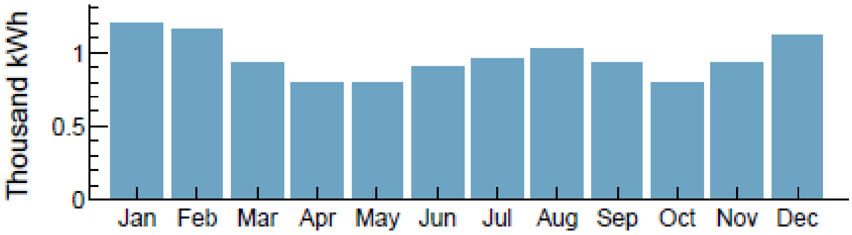
Photovoltaic System	5.18 kW Nameplate	unknown, -
Residential	$2.70/W Installed Cost	41.39 N, 2.16 E GMT +1

Year 1 Monthly Generation and Load Summary

Electricity from System



Load



Year 1 Monthly Electric Bill and Savings ($)

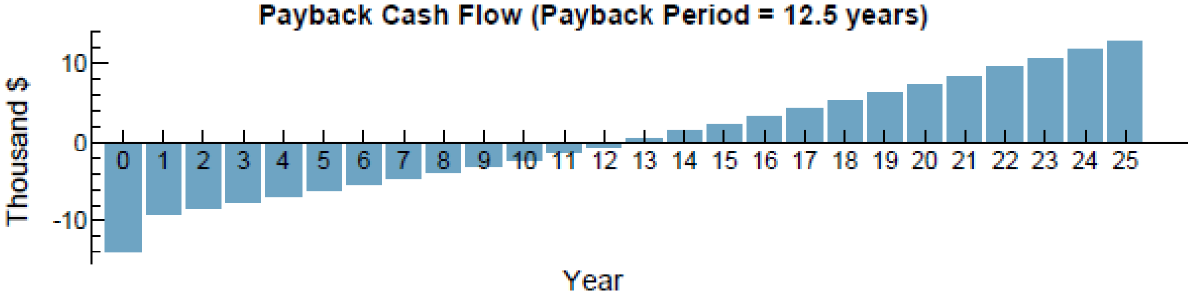
Month	Without System	With System	Savings
Jan	155	86	68
Feb	144	79	65
Mar	117	50	67
Apr	104	36	68
May	108	33	74
Jun	115	40	75
Jul	120	35	85
Aug	132	45	87
Sep	115	44	71
Oct	109	48	61
Nov	121	63	57
Dec	137	80	56
Annual	1,482	644	837

NPV Approximation using Annuities

Annuities, Capital Recovery Factor (CRF) = 0.1023		
Investment	$0	Sum:
Expenses	$-1,100	$300
Savings	$500	NPV = Sum / CRF:
Energy value	$1,000	$3,000

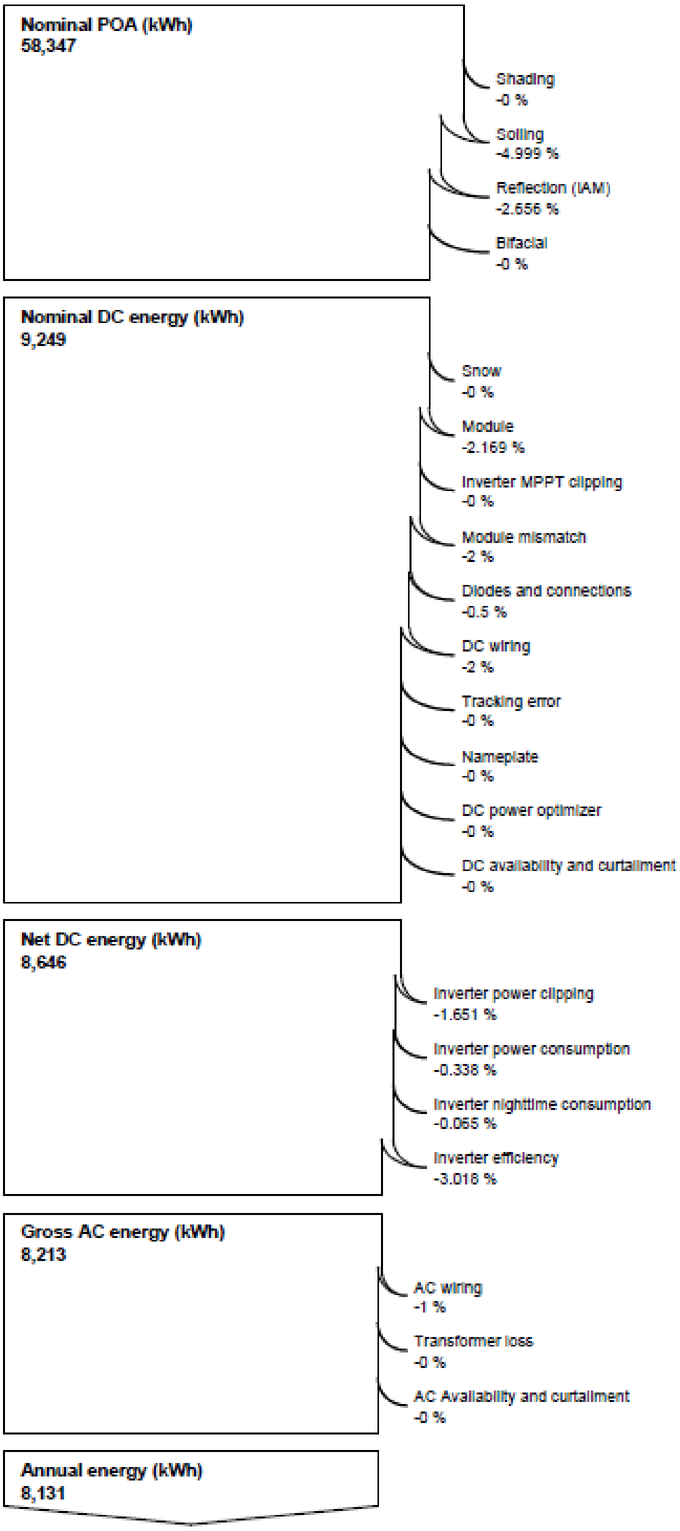
Investment = Installed Cost - Debt Principal - IBI - CBI
Expenses = Operating Costs + Debt Payments
Savings = Tax Deductions + PBI
Energy value = Tax Adjusted Net Savings
Nominal discount rate = 9.06%

Payback Cash Flow (Payback Period = 12.5 years)



Photovoltaic System 5.18 kW Nameplate unknown, -

Residential $2.70/W Installed Cost 41.39 N, 2.16 E GMT +1



Residential | Flat Plate PV | Simple Efficiency Module Model | Sandia Inverter Database

8.4 Example solar PV system 27 panel's report

System Advisor Model Report

Photovoltaic System	7.77 kW Nameplate	unknown, -
Residential	$2.70/W Installed Cost	41.39 N, 2.16 E GMT +1

Performance Model

Modules	
SolarWorld Industries GmbH Sunmodule Protect SW 285 ...	
Cell material	Mono-c-Si
Module area	1.68 m²
Module capacity	287.96 DC Watts
Quantity	27
Total capacity	7.77 DC kW
Total area	45 m²

Inverters	
SMA America: SB3800TL-US-22	
Unit capacity	3.850000 AC kW
Input voltage	100 - 480 VDC DC V
Quantity	2
Total capacity	7.7 AC kW
DC to AC Capacity Ratio	1.01
AC losses (%)	2.00

Array	
Strings	3
Modules per string	9
String voltage (DC V)	0.00
Tilt (deg from horizontal)	40.00
Azimuth (deg E of N)	165
Tracking	no
Backtracking	-
Self shading	no
Rotation limit (deg)	-
Shading	no
Snow	no
Soiling	yes
DC losses (%)	4.44

Performance Adjustments	
Availability/Curtailment	none
Degradation	0.500000 %/yr
Hourly or custom losses	none

Annual Results (in Year 1)	
GHI kWh/m²/day	4.50
POA kWh/m²/day	4.00
Net to inverter	12,960 DC kWh
Net to grid	12,400 AC kWh
Capacity factor	18.2
Performance ratio	0.83

Financial Model

Project Costs	
Total installed cost	$20,959
Salvage value	$0

Analysis Parameters	
Project life	25 years
Inflation rate	2.5%
Real discount rate	6.4%

Project Debt Parameters (Mortgage)	
Debt fraction	100%
Amount	$20,959
Term	25 years
Rate	5%

Tax and Insurance Rates	
Federal income tax	15 %/year
State income tax	7 %/year
Sales tax (% of indirect cost basis)	5%
Insurance (% of installed cost)	0.5 %/year
Property tax (% of assessed val.)	0 %/year

Incentives	
Federal ITC	30%

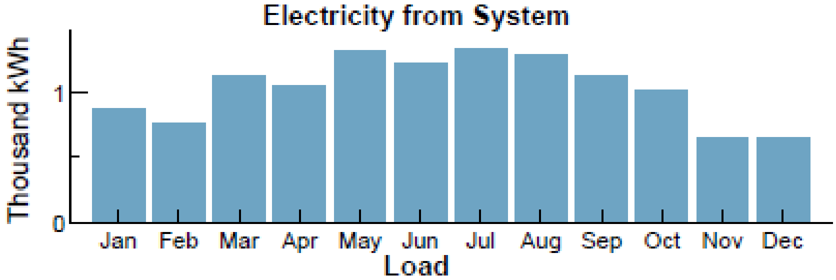
Electricity Demand and Rate Summary
Annual peak demand 3.2 kW
Annual total demand 11,529 kWh
Portland General Electric Co
Residential Time-Of-Use Service (Rate 7-TOU)
Fixed charge: $11.690000/month
Monthly excess with kWh rollover
Tiered TOU energy rates: 3 periods, 2 tiers

Results	
Nominal LCOE	8.5 cents/kWh
Net present value	$1,800
Payback period	16.2 years

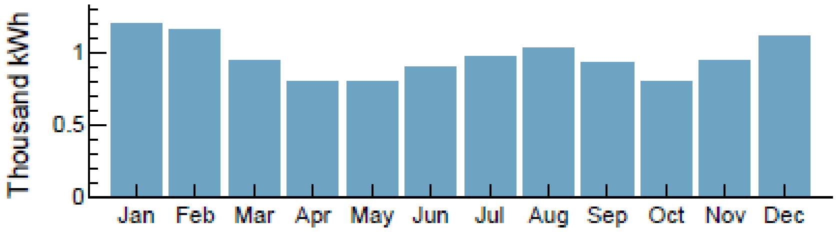
Photovoltaic System	7.77 kW Nameplate	unknown, -
Residential	$2.70/W Installed Cost	41.39 N, 2.16 E GMT +1

Year 1 Monthly Generation and Load Summary

Electricity from System



Load



Year 1 Monthly Electric Bill and Savings ($)

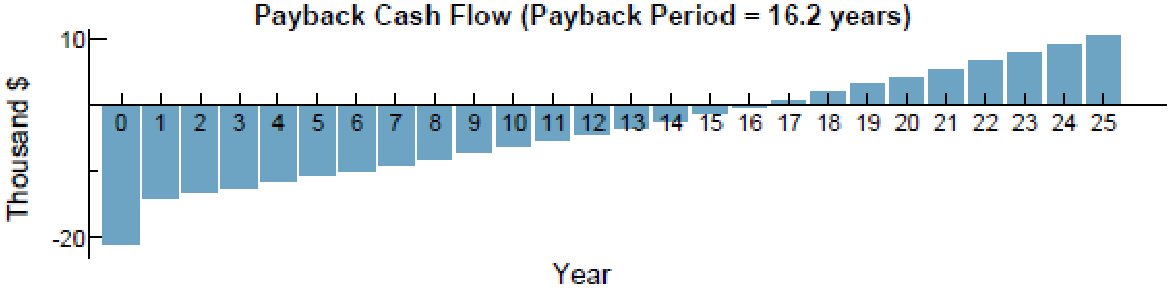
Month	Without System	With System	Savings
Jan	155	79	75
Feb	144	72	72
Mar	117	36	81
Apr	104	20	83
May	108	16	92
Jun	115	24	91
Jul	120	16	104
Aug	132	27	105
Sep	115	29	86
Oct	109	38	70
Nov	121	54	66
Dec	137	74	62
Annual	1,482	489	992

NPV Approximation using Annuities

Annuities, Capital Recovery Factor (CRF) = 0.1023		
Investment	$0	Sum:
Expenses	$-1,700	$100
Savings	$700	NPV = Sum / CRF:
Energy value	$1,100	$1,000

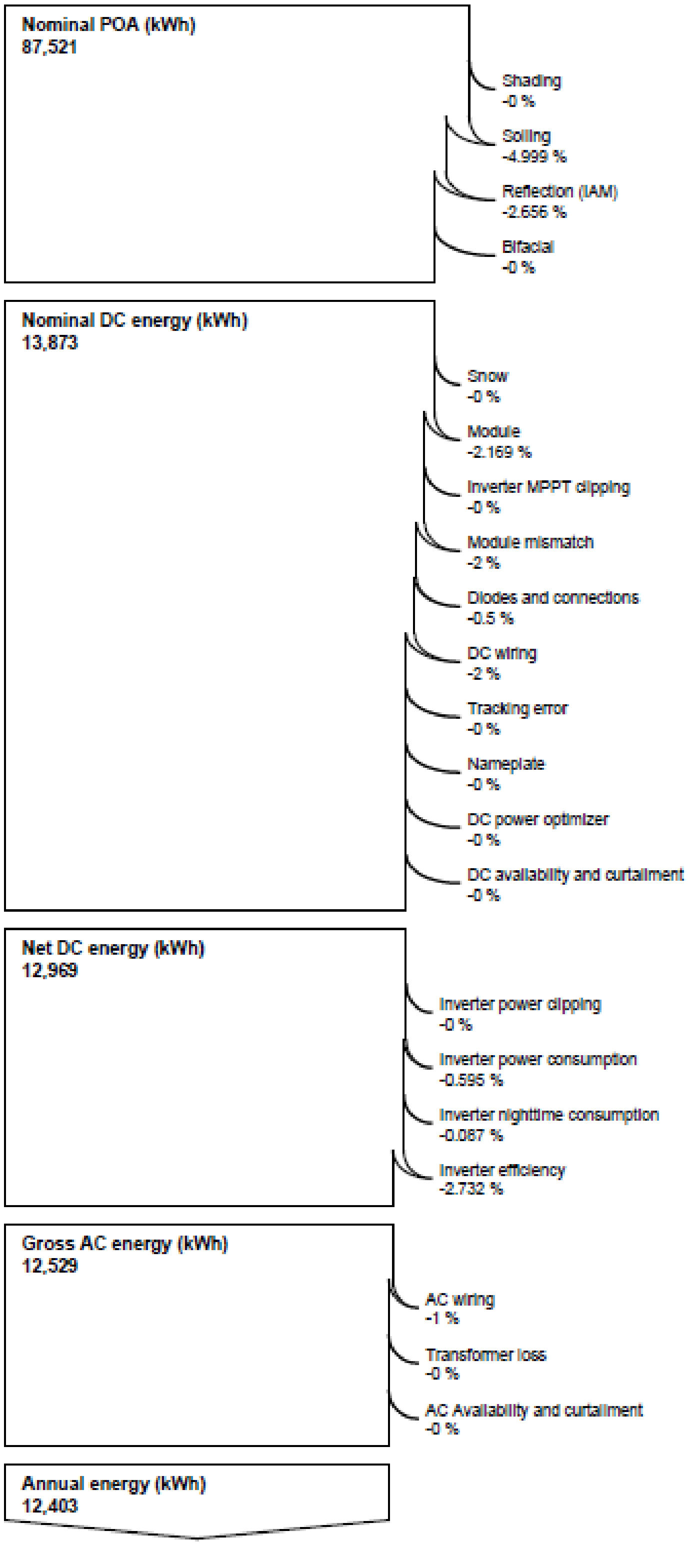
Investment = Installed Cost - Debt Principal - IBI - CBI
Expenses = Operating Costs + Debt Payments
Savings = Tax Deductions + PBI
Energy value = Tax Adjusted Net Savings
Nominal discount rate = 9.06%

Payback Cash Flow (Payback Period = 16.2 years)



System Advisor Model Standard Report generated by SAM 2018.11.11 on Sun Jun 23 13:50:05 2019 2 / 3

Photovoltaic System | 7.77 kW Nameplate | unknown, -
Residential | $2.70/W Installed Cost | 41.39 N, 2.16 E GMT +1



8.5 SolarWorld Sunmodule SW 285 Mono Datasheet [ref]

Sunmodule Plus
SW 285 MONO

SOLARWORLD
REAL VALUE

TUV Power controlled:
Lowest measuring tolerance in industry

Every component is tested to meet
3 times IEC requirements

Designed to withstand heavy
accumulations of snow and ice

Sunmodule Plus:
Positive performance tolerance

25-year linear performance warranty
and 10-year product warranty

Glass with anti-reflective coating

World-class quality
Fully-automated production lines and seamless monitoring of the process and material ensure the quality that the company sets as its benchmark for its sites worldwide.

SolarWorld Plus-Sorting
Plus-Sorting guarantees highest system efficiency. SolarWorld only delivers modules that have greater than or equal to the nameplate rated power.

25-year linear performance guarantee and extension of product warranty to 10 years
SolarWorld guarantees a maximum performance digression of 0.7% p.a. in the course of 25 years, a significant added value compared to the two-phase warranties common in the industry, along with our industry-first 10-year product warranty.**

UL 1703

ISO 9001
ISO 14001
Certified

* Solar cells manufactured in U.S.A. or Germany. Modules assembled in U.S.A.
**in accordance with the applicable SolarWorld Limited Warranty at purchase.
www.solarworld.com/warranty

MADE IN USA

solarworld.com

'SolarWorld Americas'. Accessed 23 June 2019. http://www.solarworld-usa.com/.

Sunmodule® Plus
SW 285 MONO

SOLARWORLD
REAL VALUE

PERFORMANCE UNDER STANDARD TEST CONDITIONS (STC)*

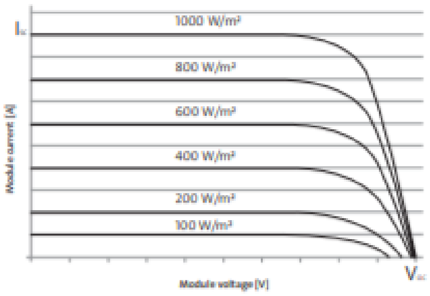
		SW 285
Maximum power	P_{max}	285 Wp
Open circuit voltage	V_{oc}	39.7 V
Maximum power point voltage	V_{mpp}	31.3 V
Short circuit current	I_{sc}	9.84 A
Maximum power point current	I_{mpp}	9.20 A
Module efficiency	η_m	17.00 %

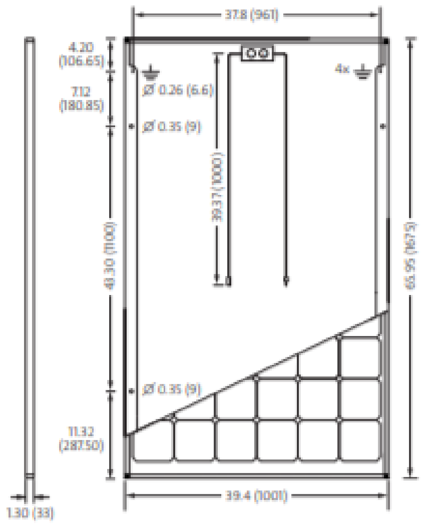
*STC: 1000W/m², 25 °C, AM 1.5

PERFORMANCE AT 800 W/M², NOCT, AM 1.5

		SW 285
Maximum power	P_{max}	213.1 Wp
Open circuit voltage	V_{oc}	36.4 V
Maximum power point voltage	V_{mpp}	28.7 V
Short circuit current	I_{sc}	7.96 A
Maximum power point current	I_{mpp}	7.43 A

Minor reduction in efficiency under partial load conditions at 25 °C: at 200 W/m², 100% of the STC efficiency (1000 W/m²) is achieved.





COMPONENT MATERIALS

Cells per module	60	*Front*	Low-iron tempered glass with ARC (EN 12150)
Cell type	Monocrystalline 5-busbar	*Frame*	Clear anodized aluminum
Cell dimensions	6.17 in x 6.17 in (156.75 x 156.75 mm)	*Weight*	39.7 lbs (18.0 kg)

THERMAL CHARACTERISTICS

NOCT	46 °C
TCI_{sc}	0.04 % / °C
TCV_{oc}	-0.30 % / °C
TCP_{mpp}	-0.41 % / °C
Operating temp	-40 to +85 °C

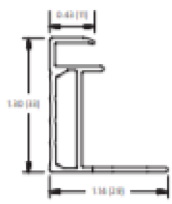
ADDITIONAL DATA

Power sorting	-0 Wp/+5 Wp
J-Box	IP65
Connector	PV wire per UL4703 with H4/UTX connectors
Module fire performance	(UL 1703) Type 1

PARAMETERS FOR OPTIMAL SYSTEM INTEGRATION

Maximum system voltage SC II / NEC		1000 V
Maximum reverse current		25 A
Number of bypass diodes		3
*Design loads**	*Two rail system*	113 psf downward, 64 psf upward
*Design loads**	*Three rail system*	178 psf downward, 64 psf upward
*Design loads**	*Edge mounting*	178 psf downward, 41 psf upward

*Please refer to the Sunmodule installation instructions for the details associated with these load cases.



- Compatible with both "Top-Down" and "Bottom" mounting methods
- Grounding Locations:
  – 4 locations along the length of the module in the extended flange.

All units provided are imperial. SI units provided in parentheses.
SolarWorld AG reserves the right to make specification changes without notice.

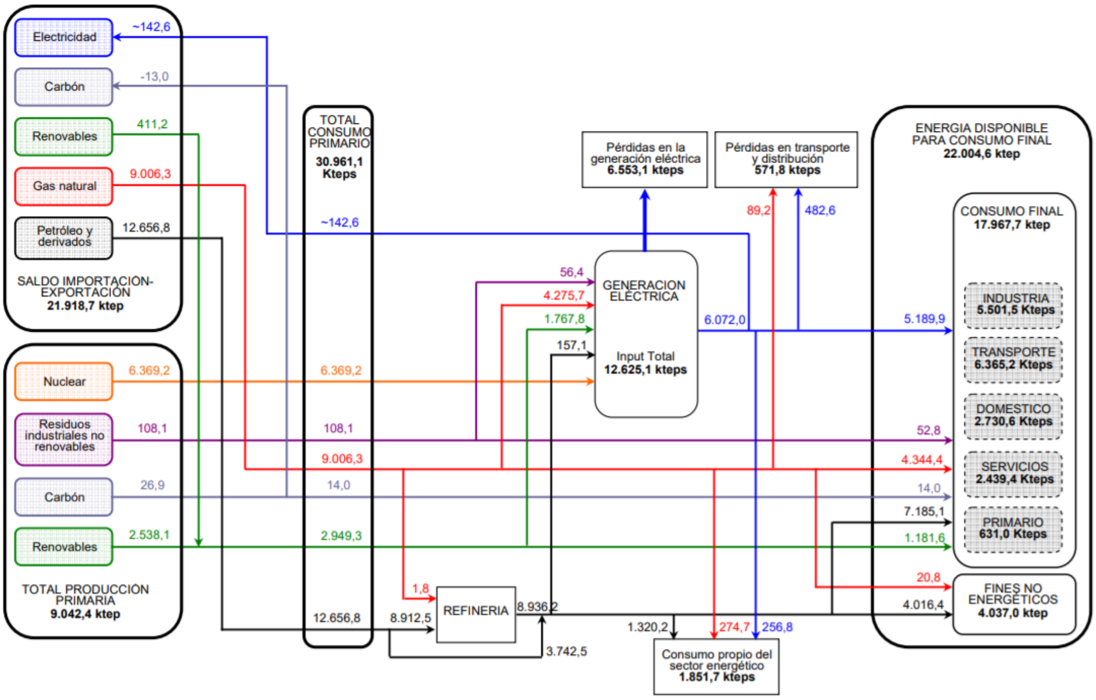
SW-01-7172US 160902

8.6 Nordex N90 – 2500 HS wind turbine Datasheet [ref]

Product Data Sheet N90/2500 (2.5 MW)

Technical specifications	
Turbine concept	Variable speed, single-blade adjustment
Rated power	2,500 kW
Rotor diameter	90 m
Hub height	70, 75, 80, 100, 120 m
Rotor	
Type	Upwind with active rotor blade adjustment
Number of rotor blades	3
Swept area	6,362 qm
Speed	9.6-16.8 rpm (LS); 10.3-18,1 rpm (HS)
Tip speed	Approx. 70 m/s (LS); 75 m/s (HS)
Rotor blade material	Glass fibre-reinforced plastic, integrated lightning protection
Tower	
Hub height	LS: 75m, 80 m, 100 m, 120 m HS: 70 m, 80 m
Operating data	
Cut-in wind speed	3 m/s
Rated power from	Approx. 13 m/s (HS), approx. 14 m/s (LS)
Cut-out wind speed	25 m/s
Generator	
Type	Double-fed asynchronous generator
Rated power	2,500 kW
Voltage	660 V
Frequency	50 or 60 Hz
Max. speed range	740-1,300 rpm
Gearbox	
Type	Two-stage planetary gearbox with one spur-gear stage or differential gearbox
Rated power	2,775 kW
Gear ratio	LS: 1:77,4 (50 Hz)/1:92,9 (60 Hz) HS: 1:71,9 (50 Hz)/1:86,3 (60 Hz)
	As of 02/2009, subject to change

8.7 Energy distribution in the Spanish country



8.8 Solar PV system installation costs

Direct Capital Costs

Module	6,945,400	units	0.3	kWdc/unit	1,999,997.4	kWdc	0.68 $/Wdc	$ 1,359,998,208.00
Inverter	1,818	units	1,000.0	kWac/unit	1,818,000.0	kWac	0.19 $/Wdc	$ 379,999,488.00
				Battery pack	0.0	kWh	300.00 $/kWh dc	
				Battery power	0.0	kW	600.00 $/kW dc	$ 0.00

	$		$/Wdc		$/m²		
Balance of system equipment	0.00		0.36		0.00		$ 719,999,104.00
Installation labor	0.00	+	0.30	+	0.00	=	$ 599,999,232.00
Installer margin and overhead	0.00		1.00		0.00		$ 1,999,997,312.00
						Subtotal	$ 5,059,993,600.00

Contingency

Contingency	0	% of subtotal	$ 0.00
		Total direct cost	$ 5,059,993,600.00

Indirect Capital Costs

	% of direct cost		$/Wdc		$		
Permitting and environmental studies	0		0.10		0.00		$ 199,999,744.00
Engineering and developer overhead	0	+	0.00	+	0.00	=	$ 0.00
Grid interconnection	0		0.00		0.00		$ 0.00

Land Costs

Land area	9,610.8	acres							
Land purchase	$ 0/acre	+	0	+	0.00	+	0.00	=	$ 0.00
Land prep. & transmission	$ 0/acre		0		0.00		0.00		$ 0.00

Sales Tax

Sales tax basis, percent of direct cost	52 %	Sales tax rate	5.0 %		$ 131,559,832.00
				Total indirect cost	$ 331,559,584.00